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THE RELATIVE SOLUBILITIES OF THE CHEMICAL CONSTITUENTS OF ROCKS

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Several years ago, while making an estimate of the rate of chemical denudation, which, from skepticism in regard to the trustworthiness of the available data, was never offered for publication, the writer was impressed with the desirability of determining, so far as might be possible, the average relative rates at which the predominant chemical constituents of rocks were taken into solution in drainage waters. So far as could be learned at the time, the problem had never been definitely formulated on a quantitative basis, nor its solution in numerical terms attempted.

The writer's aim was to obtain definite numbers which should express the relative rates at which the common oxides are dissolved by natural waters, using the oxides in the ordinary conventional sense in which they are considered as rock components. To be more explicit, the actual minerals, of which rocks are made up, were not considered at all but merely the ultimate chemical composition of rocks, expressed in terms of oxides. While the method pursued gave results suggesting interesting possibilities, it was felt that, as in the case of the problem of chemical denudation, the data available were not sufficiently trustworthy to warrant publication. At present, however, more reliable data are at hand

and, though still defective in certain respects, they afford the needed basis for a preliminary discussion of the problem.

At the outset, it should be made clear in what sense the term "relative solubilities" is used. Probably, all but the simplest minerals, when acted upon by water, do not merely dissolve, in the strict physical sense of the word, but decompose,[1] so that the constituents appear in the solution in quite different proportions from those in which they are present in the mineral. As rocks are mixtures of minerals, it is obvious that, when they are acted upon by water, there must be a very complex series of decompositions and interactions. With the details of these operations, the present inquiry is not concerned, but merely with their final results as represented by the materials in solution, derived from the rocks. For this purpose, the latter are regarded as composed, not of minerals, but of oxides, as ordinarily expressed in the results of chemical analysis. Such a conception of the rocks requires, of course, no apology, as it is necessary, and universally used, in dealing with them from the chemical point of view.

Thus, by the term relative solubilities, as here used, is meant the relative amounts of the elements, as oxides, abstracted from the rocks of the crust, by drainage waters, as compared with the amounts of the same oxides in the rocks. Obviously, this use of the word solubility is quite different from the strict sense, where a solution acts upon a homogeneous substance, without decomposition, but no other term expresses the idea as well, and such a usage is so familiar to geologists as to justify it in the present connection. A similar plea may be made for considering the oxides, the "chemical constituents" of rocks, as distinguished from the actual minerals. As before stated, these oxides are continually made the chemical units in the discussions of rocks, and this well-established custom necessitates, in the present discussion, the expression of water analyses in oxides rather than ions, as is the current custom. The use of ions for both classes of analyses would lead to the same results, but would, of course, be highly artificial, as well as unfamiliar, in the case of rocks.

[1] Cf. A. S. Cushman, and P. Hubbard, *The Decomposition of the Feldspars*, U.S. Department of Agriculture, Office of Public Roads, Bull. No. 28, p. 10, 1907.

That the constituents of rocks and minerals differ widely in their solubility is a familiar fact, made apparent by a superficial examination of rocks in the field, and emphasized by laboratory experiments, and the analysis of fresh and weathered rocks and of natural waters. As a result of investigations along these lines, it is well known that certain oxides, such as silica and alumina, are relatively resistant, while others, such as the alkalies and alkaline earths, pass somewhat readily into solution. Thus, orthoclase yields its alkalies in solution, while the silica and alumina remain in the solid state as kaolinite and quartz.

For our present purpose, this may be expressed simply as due to the greater solubility of the alkalies as compared with silica and alumina, ignoring the obvious fact that it is, in reality, a case of decomposition, not simple solution. It need hardly be said that the solubility (as the term is here used) of an oxide varies greatly with the compound in which it occurs, but the results of all such variations enter into the average relative solubility, as here discussed, without demanding any separate treatment.

Quantitative data in regard to solubilities are generally obtained by one of two very different methods. A definite amount of the rock or mineral is treated with a definite amount of water, the conditions varying with different experiments, and, by analysis of the resultant solutions, the relative amounts of the constituents dissolved are determined. This method is artificial, but, by a proper adjustment of the conditions of the experiment, may yield results of importance in interpreting natural phenomena.[1] The second method of acquiring quantitative data is to analyze fresh rocks or minerals and the corresponding residual clays or alteration products and, by a comparison of the results, to deduce the amounts of various constituents removed in solution. The first method has, thus far, been applied chiefly to minerals, but the second has been extensively applied to rocks, and has yielded results of great interest.

The two methods of investigation are essentially distinct and, while they supplement each other, do not yield strictly comparable results. In the first, or laboratory, method, a definite amount of

[1] Cf. W. P. Headden, "Significance of Silicic Acid in Waters of Mountain Streams," *Am. Jour. Sci.* (4) XVI (1903), 169–184.

the solid is treated with a definite amount of the solvent, equilibrium is established, and there is no further change of composition of either solid or solution. In nature, on the other hand, there is a continued renewal of the solvent, so that, while the most soluble constituents are first removed in relatively large quantities, the others must yield ultimately to repeated attack and the amount finally dissolved depends upon the length of time during which the process continues. Thus, to yield comparable results, the laboratory sample would have to be treated repeatedly with fresh supplies of solvent. However, this applies more especially to chemical weathering where residual clays accumulate to considerable depth and lie a long time. When secular elevation and erosion bring fresh rock within the range of solvent action, there is a tendency to compensate somewhat for the fresh supplies of solvent continually furnished, and thus to bring the conditions more nearly into harmony with those of the laboratory experiment. But an even closer approximation to the laboratory method is obtained if the entire mass of the crust traversed by meteoric waters is considered as a unit acted upon by the total body of drainage waters which, falling relatively pure upon the land areas, immediately begin to exert their solvent power and, ultimately, carry to the sea the different constituents of the crust, in varying amounts.

It was from this point of view that the problem was approached, when first considered, the composition of the crust and of the drainage waters being the basis of calculation. The former was afforded by Clarke's[1] familiar estimates of the composition of the outer shell of the crust and of the sedimentary rocks. Of the average composition of the drainage waters, only Sir John Murray's[2] preliminary estimate was available, and it was because of serious doubt as to the accuracy of these figures that publication of the results was abandoned.

While there is still much to be wished for in regard to data bearing upon the composition of drainage waters, the last few years have afforded sufficient added information in this direction to warrant renewed consideration of the problem.

[1] F. W. Clarke, *Bull. U.S. Geol. Surv., 228*, p. 19.

[2] Sir John Murray, *Scottish Geog. Mag.* (1887), p. 76.

In the present paper, the essential data used are Clarke's later estimates of the composition of the crust, and the same author's estimated mean composition of river waters.[1] The results obtained from these data are supplemented by data from other sources, as shown below.

ABUNDANT CONSTITUENTS OF ROCKS DISSOLVED IN RIVER WATERS (RECALCULATED TO 100)

	Clarke's Mean for Rivers of the Earth*	Mississippi River†	Ottawa River‡	Cache à la Poudre (Colo.)§	Feldspar Solution¶
CaO	48.34	51.05	37.12	31.12	14.43
Na_2O	14.61	16.45	9.73	21.48	7.39
MgO	9.55	15.86	12.57	7.22	1.08
K_2O	3.09	3.44	3.02	4.89	15.45
SiO_2	19.76	12.52	31.97	34.64	57.41
R_2O_3	4.65	0.68	5.59	0.65	4.24
	100.00	100.00	100.00	100.00	100.00

* Clarke's mean for the abundant constituents of the rivers of the earth.
† Mississippi River water, with Na_2O and K_2O calculated at the ratio of 4.24 to 1. Analysis by J. L. Porter. Annual average of Dole and Stabler as quoted by Clarke, *op. cit.*, p. 3.
‡ Ottawa River. Analysis by F. T. Shutt, published by R. A. Daly.
§ Cache à la Poudre, Colorado, Analysis by W. P. Headden.
¶ Feldspar Solution. Analysis by W. P. Headden.

The above constituents were recalculated to 100 per cent in order that their relative amounts in the different waters might be readily compared. For the rock analyses this was unnecessary, as the abundant constituents predominate so markedly that their amounts would be little changed by such recalculations, while, for determining the relative solubilities, it is not needed.

ABUNDANT CONSTITUENTS OF ROCKS

	Igneous Rocks*	Sediments†	Lithosphere‡	Surface Rocks§	Pike's Peak Granite¶	Feldspar**
CaO	4.81	5.42	4.82	5.27	0.74	0.314
Na_2O	3.41	1.12	3.28	1.69	3.10	2.728
MgO	3.89	2.52	3.98	2.86	.07	0.029
K_2O	2.95	2.80	2.96	2.84	5.92	11.592
SiO_2	59.99	58.51	59.79	58.88	74.90	65.760
R_2O_3	21.34	18.69	21.25	19.35	14.48	19.291

* Abundant Constituents in Clarke's estimated average Igneous Rock, *Op. Cit.*, p. 13.
† Abundant Constituents in Clarke's estimated average Sediment, *Ibid.*
‡ Abundant Constituents in Clarke's estimated average Lithosphere, *U.S. Geol. Surv. Bull. 330.* p. 31.
§ Estimated composition of "Surface Rocks," derived by combining Igneous Rocks and Sediments in the ratio of one to three.
¶ Average of Analyses of four granites from Pike's Peak Quadrangle by W. F. Hillebrand, *Journal of Geology*, VIII, 237.
** Analysis of Feldspar, Horsetooth, Col. by W. P. Headden, *op. cit.*, p. 181.

[1] F. W. Clarke, *A Preliminary Study of Chemical Denudation*, Smithsonian Coll., Vol. LVI, No. 5, p. 8, 1910.

Were the various constituents of rocks equally susceptible to the action of drainage waters, they would be carried to the sea in the proportions in which they occur in the crust. That this is far from being the case is a most familiar fact, and it is evident that they go into solution at very different rates. These rates are expressed by the ratios between the amounts of the various constituents in the rocks and in the drainage waters, respectively. That these relative rates must vary widely in different cases there can, of course, be no doubt, but the average rates are simply determined by the comparison of the compositions of the surface rocks and of the drainage waters. For the latter, Clarke's "General Mean"[1] is taken, column I, using, as in all other cases, only those constituents that are abundant in rocks.

For the rocks, the simplest method is to take Clarke's average composition of the lithosphere,[2] but this introduces an obvious source of error. This average represents a shell ten miles thick, of which probably 95 per cent consists of igneous rock. Drainage waters, being relatively superficial, exert their influence on rocks that are probably 75 per cent sedimentary and have lost certain constituents, particularly sodium, now held in solution in the sea. For this reason, it is necessary to use, as the basis of calculation, figures that allow for this permanently dissolved material. Moreover, in so far as the elements in sediments are combined differently from what they were in the crystalline rocks, their relative solubilities are doubtless affected. Correct results are to be obtained only by comparing the composition of river waters with that of the actual materials of their basins, and in the absence of precise data, the closest approximation possible must be sought.

This has been done by taking Clarke's "weighted mean"[3] of the composition of sedimentary rocks and his estimate of the composition of igneous rocks[4] and combining them in the ratios of three to one, in accord with Von Tillo's estimate of the relative areas of sedimentary and igneous rocks, the results appearing in

[1] *Op. cit.*, p. 8.

[2] "The Data of Geochemistry," *U.S. Geol. Surv. Bull., No. 330*, p. 31.

[3] F. W. Clarke, *A Preliminary Study of Chemical Denudation*, Smithsonian Misc. Coll., Vol. LVI, No. 5, p. 13, 1910.

[4] *Loc. cit.*

column II and called "surface rocks." These figures are assumed to represent the composition of the rocks leached by drainage waters, and, compared with the mean composition of the latter, column I, give the average relative solubilities of the abundant constituents of the earth's crust.

The latter values are represented by the ratios between the constituents in the water and the corresponding constituents in the rocks. These values appear in columns III and IV, in the latter recalculated to a basis of lime = 100, lime having the highest relative solubility, being an abundant constituent, and readily determined with accuracy.

The constituents are written in the order of relative solubility beginning with CaO.

	I Clarke's Mean River Water	II Surface Rocks	III Rel. Solubilities	IV Rel. Solubilities (CaO = 100)
CaO	48.34	5.27	9.17	100.0
Na_2O	14.61	1.69	8.64	96.1
MgO	9.55	2.86	3.34	36.3
K_2O	3.09	2.84	1.09	11.9
SiO_2	19.76	58.88	0.34	3.7
R_2O_3	4.65	19.35	0.24	2.6

Thus, assuming the accuracy of the figures in columns I and II, it follows that the abundant oxides of the crust are dissolved at relative rates represented by the figures of columns III and IV. Lime and soda appear to be dissolved at about the same rate, magnesia at about one-third this rate, potassa again about one-third as fast as magnesia, silica about a third as fast as potassa, and the sesquioxides about two-thirds as fast as silica. How far these figures may be trusted depends, obviously, upon the reliability of the estimated composition of river waters and of surface rocks. That these estimates will be modified in future is beyond question, and any change will, of course, affect the values of the relative solubilities. But it is believed that the figures given are a fairly close approximation to the true values, indicating, at least, the proper orders of magnitude. The most questionable figure is that for soda, since it is this constituent that is largely retained in the ocean and least likely to be accurately estimated in sediments,

where the number of analyses is limited. The other constituents cannot differ much in relative amounts in sediments and in igneous rocks. Van Hise[1] has pointed out, and explained, certain discrepancies when the analyses of the sediments are compared with those of the igneous rocks, but for the present purpose these may be overlooked. However, in view of the possible divergence of the compositions of sediments used from the true mean, it may be worth while to make a similar calculation using the composition of the igneous rocks, instead of that of the surface rocks, as above estimated. It is probable that this composition of the igneous rocks is more accurate than that of the sediments which was introduced in calculating the composition of the surface rocks, and, except for the soda, fairly accordant results might be expected, although as pointed out above, the surface rocks must differ from igneous rocks not only in bulk composition but also as to compounds present, and a comparison of the composition of drainage waters with that of the igneous rocks is, therefore, highly artificial. The results of such a comparison of the mean composition of river waters with that of the average composition of igneous rocks, are as follows:

	V Clarke's Mean River Water	VI Igneous Rocks	VII Solubilities	VIII Solubilities (CaO = 100)
CaO	48.34	4.81	10.05	100.00
Na_2O	14.61	3.41	4.28	42.5
MgO	9.55	3.89	2.46	24.5
K_2O	3.09	2.95	1.05	10.4
SiO_2	19.76	59.99	0.33	3.3
R_2O_3	4.65	21.34	0.22	2.0

Comparing the figures of columns VII and VIII with the corresponding figures of columns III and IV, the expected relations are seen, substantial agreement except for soda which shows, in column VII and VIII, decidedly smaller relative solubility. This must necessarily be the case, since the river waters actually derive their soda largely from the already depleted sediments, and if, as here done, their content be compared with that of the unleached igneous

[1] C. R. Van Hise, "Treatise on Metamorphism," *Monograph* XLVII, *U.S. Geol. Surv.* (1904), chap. xi.

rocks, a much lower, and essentially abnormal relative solubility must be obtained. While there is a tendency in the same direction for MgO, it is too slight to account for the lower figure. The fairly good agreement of the other constituents is an argument in favor of the essential reliability of the data used for the calculation, and gives added confidence in the relative solubilities of columns III and IV.

It is evident that, on the basis of solubility, the constituents fall into four distinct groups; lime and soda, magnesia and potassa, and silica and sesquioxides, although potassa might be classed with the last two, making only three groups.

It is unfortunate that alumina and iron oxide cannot be estimated separately, particularly with reference to the history of the sedimentary iron ores, but in the analyses of river waters used as the basis of calculation, they are determined together and, thus, cannot be separated here. Furthermore, these constituents occur in small quantity in waters, are difficult to determine accurately and, therefore, even when taken together, their relative solubility is open to question, although its order of magnitude is clearly fixed.

The figures of columns III and IV, then, in so far as they are accurate, express a most general relation existing between the chief chemical constituents of rocks with reference to their behavior under the solvent action of drainage waters. Based, as they are, upon analyses of the present surface rocks and existing rivers, they hold good only for existing conditions: petrologic, topographic, and climatic. A marked change of any of these conditions would produce a corresponding change in the relative solubilities, and there can be no doubt that many such changes have occurred. Doubtless, on the average, the divergence from existing values was greatest in the most remote geological times, and this must be taken into account in all considerations of chemical denudation in earlier periods. However, it is obvious that the intervals between the solubilities of the four groups are of such magnitude as to allow of considerable range, without changing the order, so much so as to make it not unlikely that the order has been the same throughout geological time.

This order, it may be noted, is in general agreement with the

order of amounts dissolved derived from the study of weathering and its solid products, as shown by Merrill,[1] Van Hise[2] and others, although that method gives no numerical relation, and its generalizations are commonly based chiefly upon igneous rocks. Van Hise calls attention to the fact that the different constituents are removed in surprisingly similar amounts, but this, of course, concerns the end result, and takes no account of relative rates of solution. As pointed out earlier, the more soluble constituents go first, so there is an ever-present tendency toward the relative concentration of the constituents of low solubilities, silica and the sesquioxides and, to a less degree, potash, in the residual clays. Were there no mechanical erosion a certain kind of equilibrium might be reached, in which residual clays would have practically uniform compositions (varying with climatic conditions) not changing with further solution. That there is a tendency to such a condition is emphasized by a comparison of the composition of residual clays, showing as they do, striking resemblances, with the widely divergent composition of rocks.

It is believed that the above figures for relative solubilities are of sufficient interest in themselves to warrant their publication, while they touch upon many problems in connection with weathering, chemical denudation, metamorphism, etc. Even upon so large a theoretical question as the composition and density of continental and oceanic areas, as discussed by Chamberlin and Salisbury,[3] they have a bearing.

While it is true that the relative solubilities given above express only a most general relation, and cannot be applied to a specific case, the simple method of comparison can be used, wherever the necessary data are available, with instructive results. From the widely varying compositions of streams and of the rocks of their drainage basins, it is clear that most divergent results must be obtained. It is only as the conditions approach the average for the entire land area that any close approximation to the mean solubilities may be expected. A few cases are appended by way of illustration.

[1] G. P. Merrill, *Rocks, Rock Weathering and Soils* (1906), p. 220.

[2] C. R. Van Hise, *op. cit.*

[3] *Geology*, II, 107.

The composition of the Mississippi River water, so far as the abundant oxides are concerned and with the soda and potassa calculated according to Clarke's[1] ratio, is given in IX, calculated to 100 from Dole and Stabler's analysis. Clarke's[2] average composition of sediments is assumed to represent the composition of the Mississippi basin. The resulting relative solubilities appear in columns XI and XII:

	IX Mississippi River	X Average Sediments	XI Solubilities	XII Solubilities (CaO = 100)
CaO	51.05	5.42	9.6	100.0
Na_2O	16.45	1.12	14.7	152.8
MgO	15.86	2.52	6.3	65.5
K_2O	3.44	2.80	1.2	12.5
SiO_2	12.52	58.51	.214	2.2
R_2O_3	0.68	18.69	.036	0.4

Compared with the figures of column VIII, there is a striking increase in the solubility of soda and magnesia. In other words, these two constituents are notably abundant in Mississippi water as compared with the amounts in the rocks, if these latter are accurately represented by the analyses used. If they are too low in the estimate used, the solubilities would come nearer the mean values. Potassa and silica are in fair accord with the mean, while the sesquioxides are low. On the whole, however, the agreement is surprisingly close in view of the fact that a single river basin is concerned, even though it be of a rather generalized type.

Another case, representing quite different conditions, is afforded by the Ottawa River, draining an area of crystalline rocks. The composition of the dissolved salts, as given by Daly[3] and recalculated to 100 per cent of abundant oxides, is shown in column XIII.

Clarke's[4] estimate of the mean composition of the lithosphere is taken to represent the composition of the Ottawa's drainage basin, column XIV, although the assumption is recognized as a rather sweeping one.

[1] *Op. cit.*, p. 9. [2] *Op. cit.*, p. 13.

[3] R. A. Daly, "First Calcareous Fossils and the Evolution of Limestones," *Bull. Geol. Soc. Am.*, XX (1909), 158.

[4] "The Data of Geochemistry," *U. S. Geol. Surv. Bull., No. 330*, p. 31.

The resultant relative solubilities are given in columns XV and XVI.

	XIII Ottawa River	XIV Average Crust	XV Solubilities	XVI Solubilities (CaO = 100)
CaO	37.12	4.82	7.70	100.
Na_2O	9.73	3.28	2.96	38.5
MgO	12.57	3.98	3.16	40.1
K_2O	3.02	2.96	1.02	13.4
SiO_2	31.97	59.79	.53	6.9
R_2O_3	5.59	21.25	.26	3.4

These figures approach most closely to those derived from comparison of the mean river water with the average igneous rocks, and differ most widely from those derived from the Mississippi River and average sediments.

The most striking variation is in the soda, which, instead of being close to lime in solubility, falls below, but close to, magnesia, thus changing the solubility groups. It is interesting to note that this order of relative solubility is the same as the order of percentage loss for each constituent for a group of nine crystalline rocks, as given by Van Hise.[1]

It would seem to be a necessary inference that, on the average, the silicates of the alkaline earths and sodium are more readily decomposed than those of potassium, aluminum and iron.

Without placing too much dependence upon either case, it seems safe to conclude that the figures for the Ottawa River roughly represent the relative solubilities for crystalline regions, while those for the Mississippi roughly represent the relative solubilities for sedimentary regions.

It is rather surprising to find the relative solubilities of soda and magnesia greater in sediments than in crystallines. While this may be due in part to the presence of more soluble compounds the essential reason probably is afforded by the rule elsewhere pointed out that, as a constituent decreases in absolute quantity in the rocks, its relative solubility increases.

The average of the solubilities derived from the Mississippi and the Ottawa is given in column XVII and the weighted mean,

[1] *Op. cit.*, p. 516.

taking the values for the Mississippi and the Ottawa in the ratio of three to one, is given in column XVIII.

	XVII	XVIII
CaO	100.0	100.0
Na_2O	95.6	124.2
MgO	52.8	59.1
K_2O	12.9	12.7
SiO_2	4.5	3.4
R_2O_3	1.9	1.1

Representing roughly the relative areas of crystalline and sedimentary rocks, the figures in column XVIII must be compared with those of IV.

The same groups appear in column XVIII, but owing to the high figure obtained for soda in the Mississippi water this constituent has changed places with lime as most soluble, while, for a similar reason, magnesia gives an abnormally high figure. Nevertheless, when the nature of the data used is considered, the agreement between these special cases and the general case is as close as could be expected.

What widely different relative solubilities may prevail in an individual case, which does not approximate to the general conditions, is shown by the waters of the Cache à la Poudre of Colorado, as analyzed by Headden[1] when compared with the average of four granites, from Pike's Peak Region, analyzed by Hillebrand,[2] which may be taken as fairly representing the stream basin.

	XIX Cache à la Poudre	XX Pike's Peak Granite	XXI Solubilities	XXII Solubilities (CaO = 100)
CaO	31.12	0.74	42.05	100.0
Na_2O	21.48	3.10	6.91	16.4
MgO	7.22	0.07	103.14	244.4
K_2O	4.89	5.92	0.84	2.0
SiO_2	34.64	74.90	0.49	1.0
R_2O_3	0.65	14.48	0.05	0.1

A mere glance at the two analyses (XIX and XX) shows a notably high content of lime and magnesia in the water as com-

[1] *Loc. cit.*

[2] E. B. Mathews, "Granite Rocks of the Pike's Peak Quadrangle," *Journal of Geology*, VIII, 237.

pared with the composition of the granite, and this is accentuated by the figures for relative solubilities (XXI and XXII).

Even the groups have been changed, and magnesia has gone far ahead, not only of soda, but also of lime, becoming conspicuously the most soluble constituent. The remaining four constituents have relative solubilities not widely different from the normal, and if multiplied by five give soda 82, potash 10, silica 5, and sesquioxides 0.5. Such divergences from the average results are only what is to be expected, indicating, as they do, how local conditions control the action of drainage waters.

Headden has laid stress upon the high silica content of this water, in which respect it is remarkable, and not only is the content of silica high, but the relative solubility is also high, as compared with soda, potash and the sesquioxides. But, from the present point of view, the striking feature is not the silica content but the relatively great lime and magnesia content, implying high relative solubilities.

As in the case of soda in the sediments, but to a much more pronounced degree, low content of lime and magnesia is accompanied by high relative solubility, and it seems probable that this relation is a general one.

This relation is particularly suggestive in connection with the problem of ore deposits, where it is always so difficult to account for the concentration, into workable bodies, of minute quantities of disseminated metals. If the 0.74 per cent of lime and 0.07 per cent of magnesia can, by the differential solvent power of drainage waters, be concentrated to 31.12 per cent and 7.22 per cent, respectively, of the abundant oxides in the water, it is safe to assume that the much less abundant metals of rocks may undergo an analogous and, perhaps, even greater, concentration, by underground waters, either meteoric or magmatic. Perhaps this relation becomes more apparent if the relative solubilities of lime and magnesia are multiplied by five, as the others were to bring them up to the normal numbers. In this case the solubility of lime is 500 and that of magnesia is 1,222.

Of course, in the ore deposit problem, it is of vital importance to know what compounds of the metals are involved, but, in spite

of the absence of such knowledge, it seems fair to infer that the minute quantities of metals that have sometimes been determined in rocks of mining districts have, because of their small quantities, higher relative solubilities than the other constituents of the rocks and thus take the first step, and perhaps a long one, toward their final concentration, when they go into solution in ground waters. The same doubtless applies to the rarer gangue materials as well.

One further special case may be added, particularly because it affords positive data as a basis of calculation, which were lacking in all the preceding cases. Reference is made to Headden's[1] experiments upon the solution of feldspar in carbonated water.

The powdered feldspar was treated with successive portions of distilled water for 48 hours, agitation being effected by a current of air containing a little carbon dioxide. Nearly 35 gallons of water were used, evaporated to dryness, and the residue analyzed. The results appear in column XXIII, the composition of the feldspar in XXIV, and the relative solubilities in columns XXV and XXVI.

	XXIII Feldspar Solution	XXIV Feldspar	XXV Solubilities	XXVI Solubilities (CaO = 100)
CaO	14.43	0.314	45.95	100.0
Na_2O	7.39	2.728	2.70	5.9
MgO	1.08	0.029	37.24	80.8
K_2O	15.45	11.592	1.33	2.9
SiO_2	57.41	65.760	0.87	1.9
R_2O_3	4.24	19.291	0.22	0.5

The agreement with the Cache à la Poudre figure is not as close as might be expected, the magnesia here occupying second place instead of first.

The relative solution concentration of magnesia, is less pronounced, for if all the figures be multiplied by five, while it gives high results for potassa, silica, and sesquioxides, the magnesia becomes only 404 as compared with 1,222. Still, the abnormally high relative solubility for constituents in small quantity is again illustrated. On the other hand, potassa shows no reduction of relative solubility as compared with soda, silica and sesquioxides,

[1] *Op. cit.*, p. 181.

in spite of its high percentage in the feldspar, while soda, present in normal quantity, is conspicuously low in relative solubility.

The wide divergences from mean relative solubilities shown by this experiment are to be accounted for on two grounds. In the first place, the conditions of the laboratory only roughly reproduced those of nature; while, in the second place, the feldspar varies rather widely from the mean composition of the rocks. The former fact may account for the relatively high solubility of potash, in spite of its large amount in the feldspar, and the low figure for soda, while the latter is doubtless responsible for the high figures for lime and magnesia.

It would be interesting to see what results would be yielded by similar experiments upon rocks representing the average surface, crystalline areas, etc., and the writer hopes that such experiments may be carried out in future. Meanwhile, the foregoing figures are presented not because they are regarded as important in themselves but rather as suggesting a promising line of investigation.

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THE COBALT SERIES; ITS CHARACTER AND ORIGIN[1]

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INTRODUCTION

In that part of northern Ontario and Quebec of which Lake Timiskaming is the geographical center, a series of pre-Cambrian clastic sediments occur which are of peculiar interest to the geologist, not only because they form the country rock of the larger part of the rich silver-bearing veins of the Cobalt mining camp, but because, as is shown in the following pages, their character is such as to indicate that they are entirely of terrestrial origin and have been deposited in part from continental glaciers. If the foregoing conclusion be correct, then another glacial period more ancient than any of those yet described in other parts of the world is added to our knowledge of the geological history of the earth, and positive evidence is afforded as to the remarkable uniformity of geological processes even in pre-Cambrian times.

In order to reach a logical conclusion as to the manner in which any series of rocks has been deposited, full information as to the character and geological relationship of the series as a whole and of all its members is necessary. The following discussion is therefore divided into two parts, in the first of which the geological relations and lithological character of the Cobalt series is described, and in the second, an application is made of those criteria from which the mode of origin of the various members of the series may be inferred.

GEOLOGICAL RELATIONS AND CHARACTER OF THE COBALT SERIES

GENERAL GEOLOGY OF THE TIMISKAMING REGION

Geologically this region belongs to the great Canadian shield of pre-Cambrian rocks which occupies the greater part of north-

[1] Published by permission of the Director of the Geological Survey branch of the Department of Mines, Canada.

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eastern North America, and corresponds in general to the Lake Superior–Lake Huron geological province. In a structural way, the rocks of the Timiskaming region may be divided into three elements which are strikingly differentiated from one another: to the first of these belong the older complex; to the second the Cobalt series (Huronian) and Nipissing (Keweenawan) diabase; and to the third the Pleistocene and Recent deposits.

The first subdivision, the older complex, consists of two classes of rocks: (1) the surficial, consisting of basic to acid volcanic flows, conglomerate, greywacke, arkose, and slate; and (2) the plutonic, consisting of granite, granodiorite, diorite, and related rocks. The rocks of the second class, as far as has been observed, are intrusive into the surficial class although the presence of pebbles and bowlders of granite in the conglomerate shows conclusively that an older granite occurs somewhere in the region and that a great erosion interval is represented.

From an examination of a general geological map of northeastern Canada, it may be seen that a wide belt of granite and related rocks (Laurentian) extends continuously from Georgian Bay to the Gulf of St. Lawrence, while to the north of this, there is a belt in which rocks of the surficial class predominate and which extends from the north shore of Lake Huron to Lake Mistassini. It seems probable that the southern granitic belt represents an ancient geanticlinal mountain core and the adjacent belt on the north a geosynclinal intermontane belt, but denudation proceeded so far in pre-Cambrian times that this synclinorium was cut off close to its base so that the surficial members of the complex are intruded by numerous small isolated batholiths of granitic rocks which have effected marked local changes in the structural trend of the rocks in their vicinity.

On the profoundly denuded surface of this ancient complex lies the second structural element, the Cobalt series (Huronian). In striking contrast with the complicated plications of the older element, the structure of these rocks is comparatively simple. They have been very slightly folded into broad, gently pitching anticlines and synclines, the dip being usually less than 20 degrees.

Along with the older complex the Cobalt series is intruded by the Nipissing (Keweenawan?) diabase which took the form of dikes in the older basement but spread out as sills in the flat-lying Huronian sediments.

The third structural subdivision, the Pleistocene and Recent deposits consist of gravel, sand, and bowlders, in the various forms assumed by glacial and fluvioglacial materials, and stratified clay and sand of postglacial lacustrine origin. These rest on the beveled surface of the Cobalt series or on the truncated surface of the older complex from which the Cobalt series has been stripped away.

THE COBALT SERIES

GENERAL CHARACTER AND SUBDIVISIONS

The Cobalt series consist of an assemblage of clastic sediments, conglomerate, greywacke, argillite,[1] arkose, and quartzite. These rocks are not sharply defined members, for they not only pass gradationally into one another, both horizontally and vertically, but conglomerate commonly occurs in the midst of greywacke or greywacke in the midst of conglomerate, and a similar relationship may exist between all the members of the series. Nevertheless, in a general way, there is a succession in most localities, from a basal conglomerate through greywacke and argillite to arkose, which in turn is overlain by an upper conglomerate.

A compilation of all the published observations of the succession and thickness of the various rocks comprising the series throughout the Timiskaming region is given in the accompanying table. Many of these sections are evidently only partial, including in some cases the upper members and in others the middle or lower. It can be seen, however, that there is generally an upper and lower conglomerate with greywacke and argillite, quartzite, and arkose as intermediate members.

[1] At the suggestion of Dr. L. V. Pirsson, the term argillite is here redefined to designate a fine grained slate-like rock which has been very firmly cemented but has no slaty cleavage. Its position in the mud-slate series corresponds very closely to that of quartzite in the sand-sandstone group.

SECTIONS OF THE COBALT SERIES IN THE TIMISKAMING REGION, ONT. AND QUE.*

Rock	Thickness	Locality	Reference
Quartzite, etc.....	1,100 feet	Timiskaming district	A. E. Barlow, *Rep. Can. Geol. Surv.*, X (1897), 104.
Slate and greywacke	100 "		
Conglomerate.....	600 "		
Slate†.....	?	Between Rabbit and Timagami lakes	G. A. Young, *Sum. Rep. Can. Geol. Surv.* (1904), p. 198,
Conglomerate.....	?		
Conglomerate.....	?	Cobalt, Ont.	W. A. Parks, *Sum. Rep. Can. Geol. Surv.* (1904) p. 211.
Quartzite.....	?		
Quartzite, etc.....	90 "	Windigo Lake	W. A. Parks, *ibid.*, p. 215.
Slate† and greywacke	90 "		
Conglomerate.....	100 "	Mount Shiminis	W. A. Parks, *ibid.*, p. 220.
Quartzite.....	135 "		
Slate†.....	315 "		
Conglomerate.....	?	Cobalt, Ont.	W. G. Miller, *Ann. Rep. Bur. Mines, Ont.* (1905), Pt. 2, p. 34.
Quartzite.....	?		
Greywacke.....	?		
Conglomerate.....	?		
Conglomerate.....	?	Larder Lake, Ont.	R. W. Brock, *ibid.*, (1907), p. 211.
Quartzite.....	?		
Slate†.....	?		
Quartzite.....	?		
Conglomerate.....	?		
Conglomerate.....	?	Claims H.R. 34 and 163 South Lorain.	A. G. Burrows, *ibid.* (1908), Pt. 2, p. 24.
Greywacke and slate†	?		
Slate†.....	?	Everett Lake Gowganda dist.	A. G. Burrows, *ibid.*, p. 10.
Quartzite.....	?		
Conglomerate.....	?		
Conglomerate.....	?	Bloom Lake	A. G. Burrows, *ibid.*
Slate†.....	?		
Conglomerate, etc....	?	Gowganda dist.	W. H. Collins, *Prelim. Rep. on Gowganda Dist.*, pp. 26 and 27; *Geol., Surv., Dept. of Mines, Can.* (1909.)
Greywacke quartzite	?		
Conglomerate.....	200+"		
Greywacke arkose, etc.	?	Montreal river district	W. H. Collins, *Sum. Rep. Geol. Surv., Dept. of Mines* (1910), p. 199.
Conglomerate.....	?		
Conglomerate.....	750 "	Kekeko hills Pontiac County, Que.	M. E. Wilson, *Prel. Mem. on Abitibi Dist., Que.*

* Sections are in descending order.

† The term slate is used for a slate-like rock without slaty cleavage—argillite.

SECTIONS OF THE COBALT SERIES IN THE TIMISKAMING REGION, ONT., AND QUE.—*Continued*

Rock	Thickness	Locality	Reference
Arkose	220 "	North end Lake Opasatika, Pontiac Co., Que.	M. E. Wilson, *ibid.*
Conglomerate	80 "		
Arkose	250 "	Swinging Hills, Pontiac Co., Que.	M. E. Wilson, *ibid.*
?	365 "		
Conglomerate	70+"		
Conglomerate	65 "	Labyrinthe Hills Pontiac Co., Que.	M. E. Wilson, *ibid.*
Arkose	165 "		
?	175 "		

Basal conglomerate.—Wherever the Cobalt series is seen in contact with the rocks of the older complex, the basal member of the series is usually a conglomerate. The outstanding feature of this basal conglomerate is its heterogeneity, not only in the size and angularity of the included fragments, but in the variability of the rock, both in texture and composition from point to point. In some places it is largely composed of coarse fragmental material with little matrix and, in other places, consists largely of matrix with few fragments. As a rule it is unstratified, but locally a partial alignment of the pebbles can be seen.

The matrix of the conglomerate varies greatly in texture and composition and may be either coarse and feldspathic or exceedingly fine grained and slate-like in appearance; the coarser types are, however, by far the most common. Examined under the microscope the matrix is seen to be composed of angular, subangular, and round fragments of quartz, feldspar, quartz porphyry, mica schist, rhyolite, andesite, basalt, and other rocks inclosed in a cement consisting chiefly of chlorite, but usually accompanied by small quantities of carbonate, epidote and pyrite (Figs. 1 and 2).

The pebbles and bowlders of the conglomerate include, even in a single rock exposure, nearly every variety of rock occurring in the older complex. Fragments of granite occur everywhere, and are commonly many miles from the nearest occurrence of this rock in the underlying basement from which the Cobalt series was evidently derived. As is generally characteristic of coarsely

clastic sediments of this character, the pebbles and bowlders are commonly subangular or angular in shape though round fragments are also present.

Greywacke and argillite.—The basal conglomerate of the Cobalt series commonly passes gradually upward by the loss of its pebbles and bowlders into greywacke and argillite. This greywacke was originally a ferromagnesian sand and the argillite a ferromagnesian mud, both of which are now, however, very firmly cemented, the

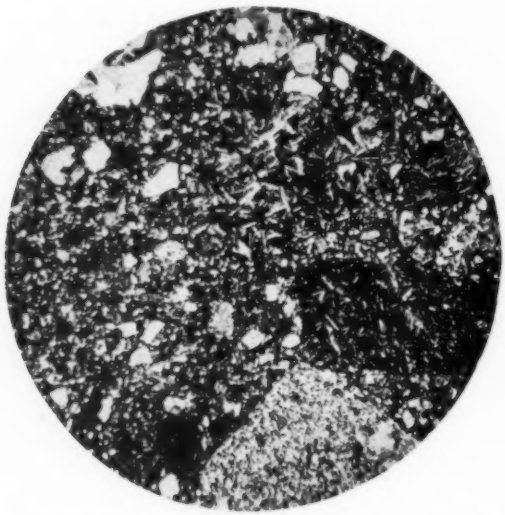

FIG. 1.—Photomicrograph of conglomerate matrix. Ordinary light. ×20

argillite resembling a slate but differing from a slate in possessing no slaty cleavage. The greywacke and argillite, like the other members of the Cobalt series, vary greatly, and here and there contain beds of arkose, masses of conglomerate, and, in some places, single isolated bowlders. In a few places the greywacke is unstratified, but as a rule both it and the argillite are uniformly bedded. The microscopic examination of the greywacke shows it to consist of fragments of quartz, feldspar, basalt, andesite, and other ferromagnesian rocks along with an abundance of chlorite.

The argillite is much finer grained than the greywacke, consisting of exceedingly minute fragments of quartz and feldspar imbedded in a chloritic cement. Small quantities of sericite, epidote, and carbonate are also commonly present in all of these rocks.

Arkose and quartzite.—The greywacke and argillite are usually replaced on passing upward by arkose or quartzite, the transition taking place by a gradual increase in the feldspar and quartz content or by an alteration of beds of the two rocks. The arkose

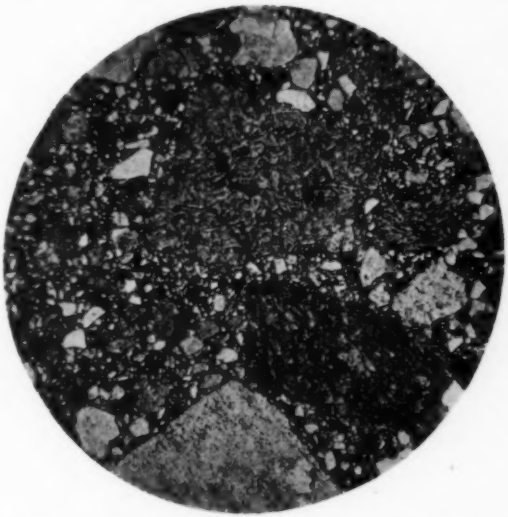

FIG. 2.—Photomicrograph of conglomerate matrix. Crossed nicols. ×20

and quartzite are firmly cemented sands which, when examined under the microscope, are found to consist of round, angular, or subangular fragments of quartz, or of quartz and feldspar along with small quantities of calcite, sericite, epidote, pyrite, and other minerals. They are generally stratified, may show ripple marks, are locally cross-bedded, and in places contain well-rounded pebbles of quartz and jasper in lenticular aggregations.

Upper conglomerate.—Wherever the Cobalt series has a considerable vertical thickness, the arkose and quartzite are overlain

conformably by an upper conglomerate which differs in no respect from the lower member of the series and cannot be distinguished from it except where the stratigraphical succession is known.

INTERFORMATIONAL UNCONFORMITIES

In his geological report on the Cobalt district, W. G. Miller subdivided the Cobalt series into Lower and Middle Huronian,[1] but more recently[2] has adopted the name Cobalt series to include both these subdivisions. Miller's classification of the Huronian into two series was based on an unconformity between greywacke and arkose occurring, on lot 4, in the twelfth concession of Lorrain Township, Nipissing district, Ontario, where angular fragments of the greywacke are inclosed in an arkose matrix. Unconformities between a "greywacke conglomerate and an overlying arkose series" are also mentioned by A. G. Burrows in a marginal note on a map of "part of the Gowganda silver area," published by the Ontario Bureau of Mines, but no details as to the character of these are given. In one locality in the Larder Lake district the writer observed an arkose bed to contain fragments of an underlying argillite, but the fragments were irregular in outline and contained sand grains along their margin as if the argillite had been plastic at the time of its fragmentation. Fragments of a precisely similar character and in the same relationship have also been observed by W. H. Collins in the region north of the Sudbury district.[3] With the foregoing exceptions, as far as has been observed, the various members of the series are in conformable relationship to one another[4] so that the unconformities that have been described are local and probably interformational in character and do not necessarily signify a break of any importance in the continuity of deposition.

DISTRIBUTION OF COBALT SERIES

The Cobalt series is now known to occur in the Timiskaming region and vicinity throughout an area of approximately 20,000

[1] *Ann. Rep. Bur. of Mines, Ont.* (1905), Pt. 2, pp. 40–42.

[2] *Eng. Min. Jour.*, XCII (1911), 648.

[3] Personal communication.

[4] *Sum. Rep. Geol. Surv., Dept. of Mines, Can.* (1906), p. 117; "Geol. of an Area Adjoining the East Side of Lake Timiskaming," *Geol. Surv., Dept. of Mines, Can.* (1910), p. 30; "Prel. Rep. on Gowganda Mining Division," *ibid.* (1909), p. 32.

square miles, but this is probably a mere fraction of its former extent for much Huronian, having the same lithological character and geological relationships, occurs in outlying districts such as that on Lake Chibougamau, about 300 miles to the northeastward.

THE PRE-COBALT SERIES PALEOPLAIN

Since the rocks comprising the Cobalt series have been but very gently folded, it follows that the surface upon which they were deposited has also not been greatly deformed, and that by the study of the contours of the contact of the basal conglomerate and the older complex, the stage, in physiographic development of the ancient erosion surface, at the time the deposition of the Cobalt series began, may be deciphered. The approximately uniform elevation, at which the junction of the Cobalt series and the older complex occurs throughout considerable areas, shows that the topography of the ancient surface was generally flat, but here and there hills consisting of rocks of the older complex occur which rise to elevations of 200 to 600 feet above the surrounding country and which must have had a still higher elevation prior to the deposition of the Cobalt series, for they have undergone denudation since that series was stripped from their surface. The ancient surface had therefore a range in elevation as great or greater than that of the region at present, but on the whole was probably more flat, the hills being local remnants which rose above the general level of erosion. This pre-Cambrian surface of denudation, therefore, represents a peneplain buried and later exposed and falls into the class of form known as a paleoplain.

THE CONTACT OF THE COBALT SERIES AND THE OLDER COMPLEX

The contact between the Cobalt series and the rocks of the older complex is peculiar in places, in that no definite line of junction can be seen, the underlying rock passing gradually upward into the basal conglomerate; in other places, however, the contact is very sharply defined, the conglomerate resting on a smoothly denuded surface. A striking example of this transitional relationship occurring at Baie des bères on the east shore of Lake Timiskaming has been described in detail by Barlow

and Ferrier.[1] Examples of the sharply defined contacts have been described by W. H. Collins and by the writer.[2]

THE ORIGIN OF THE COBALT SERIES

HYPOTHESES PROPOSED

The Cobalt series has, in recent years, been the object of special study by those geologists engaged in fieldwork in the Timiskaming region for the purpose of procuring evidence which would confirm or disprove the glacial hypothesis which has been strongly advocated by A. P. Coleman in a number of recent publications.[3] With this object in view, the writer, while in the field, paid special attention to those characteristics of the various members of the series which might have a bearing on the conditions under which they were deposited, hoping in that way to reach some definite conclusions as to their origin.

That the conditions under which the series was deposited were unusual is indicated by the various modes of origin which have been suggested from time to time, by the geologists who have studied these rocks in the field. Owing to the fact that the earlier geologists did not distinguish the Cobalt series from the underlying Abitibi group[4] (Keewatin), the conglomerate was thought to be closely related to the lavas of the underlying basement and were said to be of pyroclastic origin,[5] although it was noted that many fragments of granite and other plutonic rocks were present. In 1905, A. P. Coleman in his report[6] on the Sudbury nickel field,

[1] "On the Relations and Structures of Certain Granites and Associated Arkoses on Lake Timiskaming, Canada," *Rep. B.A.A.S.*, Toronto (1897), pp. 656–60; *Ann. Rep. Geol. Surv. Can.* (1897), pp. 195–99, 1.

[2] "Prel. Rep. on Gowganda District, Ont." *Geol. Surv. Bran., Dept. of Mines, Can.* (1909), p. 31; "The Larder Lake District, Ont., and Adjoining Portions of Pontiac County, Que." *Mem. 17, Geol. Surv., Dept. of Mines, Can.*, 1910.

[3] *Amer. Jour. Sci.*, XXIII, 187–92; *Bull. Geol. Soc. Amer.*, XIX, 347–66; *Jour. Geol.*, XVI, 149–58.

[4] The name Abitibi group is here used for those surficial rocks of the older complex occurring in the Timiskaming region, whose stratigraphical and structural relations are as yet unknown.

[5] *Ann. Rep., Can. Geol. Surv.*, X (1897), 96.

[6] *Ann. Rep. Bur. of Mines, Ont.*, XIV (1905), Pt. 3, p. 1289.

pointed out the resemblance of a greywacke conglomerate, occurring in the vicinity of Ramsay Lake, to bowlder clay; and in the same year, W. G. Miller mentioned the possibility of a glacial origin for the conglomerate of the Cobalt series, but also suggested desert conditions of deposition in the following quotation. "The writer is not able to offer a satisfactory explanation for the character of the sediments found in some of these strata. . . . . To account for the undecomposed and angular character of much of the fragmental material, the writer is inclined to the belief that desert conditions prevailed in this region at the time some of the middle Huronian rocks, at least, were formed."[1] R. W. Brock in his report on the Larder Lake District published in 1907,[2] noted some characteristics of the rocks favorable to the glacial hypothesis but concluded that there were still difficulties in the way of its acceptance. He also observed that many of the included fragments had the form of bowlders worn by river sands.

APPLICATION OF CRITERIA

Although the various suggestions in the above quotations all imply a continental origin, none of these writers have pointed out the many characteristics of the series which point to terrestrial conditions of deposition. The great heterogeneity and general absence of complete sorting throughout the greater part of the series, the presence of ripple marks, current marks, cross-bedding, and interformational unconformities, the presence of an ancient soil at the base of the conglomerate in places, the angularity or subangularity of the fragmental material comprising the series, and the great thickness and enormous extent of the conglomerate are features distinctly characteristic of land sediments. It shall therefore be assumed without further discussion that the Cobalt series is of terrestrial origin, the term terrestrial implying deposition on the land in contrast with deposition in the sea or on the seashore.

Continental clastic sediments may be formed by volcanic action or by weathering, creepage, lakes, rivers, winds, or glaciers,

[1] *Ann. Rep. Bur. of Mines, Ont.* (1905), Pt. 2, p. 41.

[2] *Ibid.*, XVI (1907), 212.

the degree of importance and relationship of the latter agencies to one another depending, in part, on climate, and in part, on the topography of the land.[1]

In the following discussion I shall apply some of the criteria which characterize sediments originating in these various ways to the different members of the Cobalt series, and in that way attempt to reach some conclusions as to the climate and conditions of deposition prevailing during this Huronian period.

1. *Pyroclastic origin.*—Owing to the misunderstanding of the relationship of the Huronian of the Timiskaming region to the volcanic rocks of the older complex, the conglomerate of the Cobalt series was at one time thought to be of pyroclastic origin but it is now known that it is almost, if not entirely,[2] composed of material derived from the underlying floor. This mode of origin need not therefore be considered.

2. *Weathering and creepage.*—Since weathering and creepage are closely related processes operating together, for the purpose of this discussion they may be considered as one.

The indefinite contacts which occur at the base of the Cobalt series, in places, indicate that at the time the deposition of the series was initiated, the surface of the ancient complex was covered by a considerable thickness of soil and that this has been preserved so that the basal beds of the conglomerate at these points represent a fossil regolith, developed *in situ* by weathering.

This ancient soil consisted of disaggregated, undecomposed rock fragments, a feature from which some inference may be drawn as to the climate prevailing at the time it was formed. The domination of disintegration over chemical decomposition, on the earth's surface today, is characteristic of regions[3] of youthful topography, is also characteristic of arid climates[4] and to a lesser extent of cold

[1] J. Barrell, *Jour. Geol.*, XVI (1908), 159; A. Penck, *Amer. Jour. Sci.*, XIX (1905), 166.

[2] *Ann. Rep. Bur. of Mines* (1905), Pt. 2, p. 47.

[3] B. Willis, *Jour. Geol.*, I (1893), 477.

[4] E. Pumpelly, *Geol. Soc. Amer.*, XVI (1908), 167; J. Barrell, *Jour. Geol.*, XVI (1908), 167.

or temperate climates,[1] but is not characteristic of warm humid climates.[2] Since this region, at the time the soil was formed, was practically a peneplain, the topographic factor may be eliminated. If it be assumed, therefore, that the variations in the conditions for soil development were the same in pre-Cambrian times as at present, the climate which preceded the deposition of the Cobalt series was either cold and humid, temperate and humid, or arid.

It is possible that owing to the absence of abundant vegetation to supply carbon dioxide to the ground water, or because of differences in the composition of the atmosphere, the relationship of the chemical decay in the soil to climate may have been somewhat different at that early period, but it is doubtful whether this would be of sufficient importance to modify the foregoing conclusion. The abundance of limestone in some of the early pre-Cambrian formations indicates that carbon dioxide was certainly present in the atmosphere at the very beginning of geological time and may have been more abundant than in later periods, for it seems probable that the loss of carbon dioxide from the atmosphere through the formation of limestone and coal beds, since the pre-Cambrian, has been greater than the additions from other sources.

3. *Lacustrine deposition.*—The uniformly stratified argillite, greywacke, arkose, and quartzite which form a considerable part of the Cobalt series were evidently deposited from standing bodies of water and are therefore flood-plain or lacustrine deposits. However, from the general greenish-grey or green color of all these sediments, from the absence as far as has been observed of mud cracks, rain prints, or other evidence of exposure to the air,[3] in even the fine grained argillite, and from the presence of uniformly continuous ripple marks in the quartzite, it seems safe to conclude that these deposits have not been laid down from either flooded rivers or ephemeral lakes, but were deposited from permanent bodies of water which persisted from year to year.

[1] I. C. Russell, *Bull. 52, U.S. Geol. Surv.* (1888), p. 12; G. P. Merrill, *Bull. Geol. Soc. Amer.*, VI (1895), 321–22.

[2] E. W. Hilgard, *Soil* (1906), 398–417.

[3] J. Barrell, *Jour. Geol.*, XVI (1906), 538; J. Walther, *Einleitung in die Geologie* (1897), p. 846.

With regard to the characteristics of these sediments which have a climatic significance, it may be observed from the features mentioned in the previous paragraph, that these, in general, point to humid rather than to arid or semiarid conditions of deposition. Furthermore, bowlders occur in places in the midst[1] of fine grained, stratified greywacke and argillite, a condition which seems to necessitate the presence of floating ice. From this, it may be inferred that the climate of this period was not only humid but cold.

4. *Aeolian deposition.*—Since the greater part of the finer grained material comprising the Cobalt series is uniformly bedded, it is evident that these are subaqueous deposits. Moreover it was pointed out in the previous paragraph that the climate, at the time these materials were laid down, was probably cold and humid. Consequently it may be inferred that aeolian action was never a depositional factor and probably played little or no part in the formation of the series.

5. *Fluviatile deposition.*—The general great heterogeneity of the conglomerate of the Cobalt series, the great variability in the matrix, in the size of the pebbles, and bowlders, and in the rock types represented in the conglomerate, the varying degree of abrasion to which the pebbles and bowlders of the conglomerates have been subjected, the presence of cross-bedding in places are all characteristics commonly pertaining to sediments of a fluviatile origin which have been deposited not far from the source of supply. The conglomerates of the Cobalt series have therefore the essential characteristics of fluviatile deposits.[2]

Notwithstanding, however, the apparent similarity of the conglomerates of the Cobalt series to river deposits, there are some features associated with these which are inconsistent with a fluviatile origin. A considerable part of the bowlders contained in the conglomerate, in places, are 2, 3, or even 8 feet in diameter[3] and are commonly many miles from the nearest occurrence of similar rocks in the older complex. Moreover, the surface upon which

[1] A. B. Coleman, *Jour. Geol.*, XIV (1908), 153.

[2] C. R. Mansfield, *Jour. Geol.*, XV (1907), 550–55.

[3] *Jour. Geol.*, XVI (1908), 151; "Prel. Rep. Gowganda Min. Div.," *Geol. Surv., Dept. of Mines, Can.* (1909), p. 27.

the conglomerate was deposited was one of mature topography, so that the transportation of the large bowlders must have been effected by streams having gentle gradients. In order to explain this difficulty, it has been pointed out[1] that the climate of this Huronian period may have been semiarid and that during floods in regions where such climatic conditions prevail, bowlders of

FIG. 3.—Scratched and faceted pebble from the conglomerate of the Cobalt series, occurring in Boischatel Township, Pontiac County, Quebec—a point about 60 miles northeast of the Cobalt district.

large size may be transported long distances by rivers. But it has already been shown from the character of the greywacke, argillite, arkose, and quartzite associated with the conglomerate, that the climate at the time these rocks were deposited was certainly not arid and was probably humid and cold. Furthermore,

[1] *Ann. Rep. Bur. of Mines, Ont.*, XIV (1905), Pt. 2, p. 47.

the green or greenish-gray color which is everywhere characteristic of the conglomerate is not the color which usually distinguishes more recent fluviatile gravels developed in arid or semiarid regions, so that unless the pre-Cambrian atmosphere was deficient in oxygen this feature also points to humid climatic conditions. Fluviatile conglomerates of the coarse unsorted types which are characteristic of the Cobalt series are limited on the earth's surface at present to regions of youthful topography or arid climates.[1] These factors, usually operating together, have resulted in the building up of immense accumulations of river gravels on piedmont slopes and in interior basins. If it be assumed, therefore, that the conglomerates of the Cobalt series are of fluviatile origin, this conclusion must be reached in the face of the facts that these immense deposits covering a minimum area of 20,000 square miles were built up in a region having a low relief and a pluvial climate, conditions which in every particular are the reverse of those under which similar fluviatile deposits are accumulating on the earth today.

6. *Glacial deposition.*—In a number of papers published within the last few years, A. P. Coleman has advocated the glacial origin of the conglomerates of the Cobalt series, pointing out their striking similarity to the Pleistocene glacial deposits and to similar rocks in other parts of the world to which a glacial origin has been assigned. The principal features emphasized by Coleman are the resemblance of the matrix of the conglomerate to bowlder clay; the enormous extent and great thickness of the conglomerate; the occurrence of immense bowlders at a distance of several miles from the source of supply; the great size, angularity and variety of the pebbles and bowlders of the conglomerate; and, finally, the finding of scratched and "soled" pebbles and bowlders in the conglomerate at Cobalt, Ont.[2]

[1] Medlicott and Blanford, *Geology of India*, p. 397; Huntington, *Carnegie Inst. Exploration in Turkestan*, p. 40; J. Barrell, *Jour. Geol.*, XIV (1906), 330; A. C. Trowbridge, *ibid.*, XIX (1911), 738; E. W. Hilgarde, *Sci.*, N.S., XV (1902), 414; N. S. Shaler, *Bull. Geol. Soc. Amer.*, XII (1907), 271–300; I. C. Russell, *Geol. Mag.*, VI (1886), 289–95; J. L. Rich, *Jour. Sci.*, XVIII (1910), 601–32.

[2] *Amer. Jour. Sci.*, XXIII (1907), 187–92; *Jour. Geol.*, XVI (1908), 149–58; *Bull. Geol. Soc. Amer.*, XIX (1908), 347–466.

As opposed to the glacial hypothesis, it has been maintained that glaciated surfaces should somewhere be found beneath the basal conglomerate instead of the ancient regolith which is commonly present.[1] In reply to this objection, Coleman has pointed out that "near the edge of a glaciated area where the thickness of ice is not great, the ice sheet often moves for many miles over loose material without ever reaching the rock surface beneath," and that this condition existed over thousands of square miles in certain parts of the United States during the Pleistocene continental glacial epoch and also throughout a large part of the area covered by carboniferous bowlder clay in India.[2] It must, furthermore, be recalled that the number of points at which the junction of the Cobalt series and the underlying basement has been examined is not great and that, at some of these, the contact is sharply defined, the conglomerate resting on a smoothly eroded surface. The latter might well be glaciated surfaces, although stream erosion or wave action might no doubt produce a similar effect.

Owing to the firmly cemented character of the conglomerates of the Cobalt series, it is difficult to separate the pebbles and bowlders from their matrix, but during the summer of 1911 an exceptionally favorable locality was found at the eastern end of the Kekeko Hills in Boischatel Township, Que., where Mr. E. M. Burwash, who assisted the writer in the field, succeeded in breaking out some pebbles from the conglomerate which were definitely scratched in several directions (Fig. 3). The conglomerate at this point lies almost horizontal and has been neither mashed nor faulted, so that the scratches cannot be attributed to dynamic action.[3] The pebbles exhibiting the scratches consist of fine grained greenstone and possess the typical rounded corners and faceted faces of glacial stones.

In order to obtain further definite evidence bearing on the glacial origin of the Cobalt series, an attempt was made to count the "soled" pebbles and bowlders in the conglomerates. Only those stones having rounded corners and two or more plane faces,

[1] *Ann. Rep. Bur. of Mines, Ont.*, Pt. 2, p. 58; *Can. Min. Jour.*, XXX, 646–97.

[2] *Jour. Geol.*, XIV (1908), 155; *Can. Min. Jour.*, XXX, 694.

[3] *Ann. Rep. Bur. of Mines, Ont.* (1907), Pt. 2, p. 58.

which, when projected, intersected at a considerable angle, were counted, but since it was not possible to break out the pebbles and bowlders for examination on all sides, the count was made from observation of the outlines exhibited in a given area of rock surface. The results obtained were as follows:

Total Number of Pebbles and Bowlders	Number of Soled Pebbles and Bowlders	Percentage	Locality
205	17	8	Destor Township, Pontiac Co., Que.
210	37	18	Kekeko Hills, Boischatel Township, Pontiac Co., Que.
99	38	38	Labyrinthe River, Dasserat Township, Pontiac Co., Que.
168	54	26	Labyrinthe Hills, Dasserat Township, Pontiac Co., Que.
200	60	30	N. shore Larder Lake, Hearst Township, Nipissing District, Ont.

If it had been possible to break out the pebbles and bowlders and observe them in three dimensions instead of one, the above percentages would certainly be greatly increased.

In the preceding discussion of the glacial hypothesis, attention has been confined to the conglomerates of the series. One of the strongest arguments, however, in favor of Huronian continental glaciation is to be found in a comparison of the series as a whole, to the Pleistocene glacial, fluvioglacial, and postglacial deposits of the same region—for each of these has its exact counterpart in the Cobalt series. At the base of the latter, there is the conglomerate, which, like the Pleistocene glacial drift, is exceedingly variable in thickness, and like the drift is unstratified, in part, resembling till, is rudely sorted and cross-bedded, in part, similar to the fluvioglacial deposits of kames, eskers, and outwash plains, and, in places, passes into unstratified greywacke containing scattered pebbles and bowlders, thus duplicating bowlder clay.[1] Overlying the basal conglomerate, there is the stratified greywacke, argillite, arkose, and quartzite which have their parallel in the Pleistocene postglacial stratified clay and sand of lacustrine

[1] "Prel. Rep. on Gowganda Dist.," *Geol. Surv., Dept. of Mines* (1909), p. 26.

origin.[1] In both of these deposits, bowlders have been found which have been attributed to floating ice.[2] The Cobalt series differs from the Pleistocene deposits of northern Ontario and Quebec in the greater thickness of arkose and quartzite which it contains and in the presence of an upper conglomerate[3] overlying the finer grained members of the series. These conditions, however, would simply imply that the lake which covered the region subsequent to the deposition of the basal conglomerate was of longer duration than that of the Pleistocene, and that following the lacustrine epoch a second continental ice sheet advanced over the region from which an upper conglomerate was laid down. If it be assumed, therefore, that the conglomerates of the Cobalt series are of glacial origin, then there are at least two till sheets present, and the stratified greywacke, argillite, quartzite, and arkose constitute interglacial deposits.

The essential similarity of the greywacke and argillite of the Cobalt series to the postglacial lacustrine clays of the region is shown in the following table of chemical analyses. Column I is an analysis of the argillite and column II that of the stratified clay

	I	II	III	IV	V
SiO_2	62.74	52.00	64.81	57.94	61.54
Al_2O_3	16.94	16.11	17.48	17.92	.....
Fe_2O_3	5.07	4.69	5.23	5.83	.....
FeO	1.59		1.64		.....
MgO	3.05	4.10	3.14	4.56	.....
CaO	1.39	8.26	1.43	9.20	.84
Na_2O	6.07	2.76	6.27	3.09	4.73
K_2O		1.74		1.95	2.84
H_2O-	.36	9.64	.....	.....	.....
$HO+$	3.20	.....	.....	.....	.....
SO_3	.....	.09	.....	.10	.....

I. *Ann. Rep. Bur. of Mines, Ont.*, XIV (1905), Pt. 2, p. 48.
II. *Ibid.* (1905), p. 33.
III. I recalculated to a total of 100 omitting water.
IV. II recalculated to a total of 100 omitting water.
V. *Jour. Geol.*, XVIII (1910), 669.

[1] *Ann. Rep. Bur. of Mines, Ont.*, XIV (1905), Pt. 2, p. 33; XVIII (1908), 282, 284; *Sum. Rep. Geol. Surv., Dept. of Mines, Can.*, 1911.

[2] *Jour. Geol.*, XVI (1908), 153; *Ann. Rep. Bur. of Mines, Ont.*, XX (1911), Pt. 1, p. 220.

[3] See table, pp. 124, 125.

occurring at the north end of Lake Timiskaming. In order to make these more nearly comparable, they have been recalculated to a total of 100 omitting the water. In Column V a partial analysis of argillite from Lily Lake in the Gowganda district, is inserted.

It will be observed that in both the argillite and the clay there is an excess of soda over potash, a relationship which is usually reversed in normal sediments of the slate-shale series. The large percentage of lime and magnesia in the postglacial lacustrine deposits is undoubtedly due to the large amounts of Paleozoic limestone which were denuded away by the Pleistocene continental ice sheets and were thus transformed into glacial drift and later redeposited as stratified clay.

CONCLUSION

Having assembled the evidence which might have a bearing on the origin of the Cobalt series, the following conclusions may be cited with regard to the climatic conditions and depositional processes in operation at the time these sediments were laid down: (1) that the series is of terrestrial origin; (2) that the basal portion of the series is in places an ancient regolith; (3) that the stratified greywacke, argillite, quartzite, and arkose are lacustrine deposits; (4) that aeolian deposits are not represented in the series; (5) that the climate of this period was *not* arid or semiarid and was probably cold and humid. (6) With regard to the mode of deposition of the major part of the conglomerate only two hypotheses need be considered. They are either of fluviatile origin or have been deposited from continental ice sheets. From a consideration, however, of the difficulties of transportation involved in the fluviatile hypothesis and that the climate and topography of the region were wholly the reverse of those under which fluviatile deposits of this character are accumulating on the earth today, and on the other hand, the facts that practically every feature of the Cobalt series has its duplicate in the Pleistocene glacial, interglacial, or postglacial deposits of North America, that the pebbles and bowlders of the conglomerates have a characteristically "soled" appearance and that striated pebbles and bowlders have been found in two localities over 60 miles apart, it seems necessary to

conclude that the evidence preponderates in favor of the hypothesis that the conglomerates of the Cobalt series were deposited from pre-Cambrian continental ice sheets.

In the above pages an attempt has been made to apply the criteria which distinguish the various types of continental clastic sediments to the different rock types represented in the Cobalt series and thereby to reach a definite conclusion with regard to their origin. As a result it has been shown that not only has every variation in the series its duplicate in the glacial, interglacial, or postglacial deposits laid down in association with the Pleistocene continental ice sheets of the same region, but that no other known depositional process will so well account for all the many peculiarities and associations of sediments found in the series as the glacial hypothesis. Furthermore, the objection that striated surfaces have not been found beneath the basal conglomerate loses much of its force when it is recalled that only an exceedingly small part of the contact between the Cobalt series and the older complex has been observed, that the underlying surface in some places has been smoothly eroded, and that the presence of the overlying conglomerate at those points generally makes an examination for striae impracticable.

With the progress of detailed geological investigation in regions where pre-Cambrian rocks occur, evidence is accumulating which indicates that the processes at work on the earth's surface today were in operation in the very earliest pre-Cambrian periods. The existence of pre-Cambrian continental ice sheets would therefore be simply another link in the chain of evidence pointing to the uniformity of natural processes from the very earliest time in the earth's history of which we have any knowledge.

THE LATER CENOZOIC HISTORY OF THE WIND RIVER MOUNTAINS, WYOMING

LEWIS G. WESTGATE AND E. B. BRANSON

INTRODUCTION

The Wind River Mountains of West Central Wyoming run from Union Pass on the north, for over one hundred miles southeast to the Sweetwater River near Atlantic City. The range rises from the plains level of 5,000 to 6,000 feet on the east, to a crest line which in a number of places stands over 13,000 feet above the sea. Wind River Peak is 13,500, and Gannett Peak, the highest summit in the range, 13,785 feet above the sea.

The continental divide follows the crest of the range. On the east the drainage is by the Wind River and Platte and its tributaries to the Missouri and the Atlantic. Along the west side, except at the south end where the drainage is by the Sweetwater to the North Platte and the Atlantic, the streams are tributary to the Green River, thence following the Colorado to the Pacific.

Geologically the structure of the range is similar to that of the Big Horns and the Black Hills, and consists of a central axis of crystalline rocks, circled by belts of upturned Paleozoic and Mesozoic rocks, beyond which lie the nearly level Tertiaries. Along most of the east side of the range the conditions in the Black Hills are exactly reproduced, but along much of the south and west sides the Tertiaries overlap the Paleozoics and rest directly against the crystallines. Where all the formations are present each plays a distinctive part in the topography. The crystalline rocks form the central part of the range. The Paleozoics form the main foothills and slopes up to 9,000 or 10,000 feet, while the Mesozoics and Cenozoics underlie the plains. The lowest Mesozoic and highest Paleozoic, the Chugwater Red Beds, which are mainly sandstone, often make prominent ridges, rising 1,000 to 1,500 feet above the neighboring valleys, facing the range, and sometimes separated from it by a conspicuous red valley, worked out on the softer

shales which comprise the lower part of the Chugwater. In the Cretaceous certain sandstones make low ridges, but not at all comparable with those made by the Chugwater. When the Paleozoics are concealed by the Tertiary overlap the topography is simpler, and the rise from plains to mountains more abrupt.

The observations which are recorded in this paper were made in August and September, 1911, on a trip along the base of the range from the headwaters of the Sweetwater River on the west to Bull Lake Creek on the north, with side trips into the range and out onto the plains. The time which could be given to the work was far from sufficient to determine the history of the range fully, and many questions which came up had to be left unanswered. It is thought, however, that the general history of the range, as read in its topography and that of the surrounding plains, has been made out, and that the results are worth making public. We are glad to be able to express our appreciation of the courtesy of Mr. N. H. Brown of Lander, whose maps of Fremont County and of the vicinity of Lander were used in our work. The Fremont quadrangle is the only topographic sheet published by the U.S. Geological Survey which covers any part of the Wind River Mountains. As our field work was to the south of that area, and we were without topographic maps (except those of the Hayden Survey, which were too generalized for our uses), we were obliged to get altitudes by the use of aneroids, and with less opportunity than we would have wished to check such observations by bench marks.

SEDIMENTARY HISTORY: CAMBRIAN TO EARLY TERTIARY

Before the end of Cambrian time a wide transgression of the sea brought conditions of marine sedimentation over the area of the present Wind River Mountains, and from then on to the close of the Mesozoic there was almost continuous sedimentation. If at times deposit was interrupted, as seems probable from the failure to find Silurian and Devonian beds in the series, this did not interfere with the production of an essentially parallel series of sedimentary rocks. The youngest rocks found in the Lander region are the Mancos shale[1] (Colorado), over 6,000 feet, and the Mesa

[1] Woodruff, *Bulletin U.S. Geol. Survey, No. 452*, p. 10.

Verde (Montana), 2,000 feet. At the close of the Cretaceous came the uplift by which the present anticlinal structure of the range was produced. Parallel to the main uplift, and about six to eight miles east from the base of the range, is an anticlinal uplift which brings the Triassic, Jurassic, and Dakota Cretaceous out from under the Mancos shale, producing an interrupted line of hills (especially south of Lander), and forming a longitudinal valley southeast from Lander. This valley is now drained by a number of transverse streams, but this has apparently not always been the case.

Extensive erosion followed the uplift of the region, even before the time of its earliest Tertiary rocks, for we find the Wind River Tertiaries lying on the upturned and eroded edges of the Mesozoic rocks. In early Eocene times, this erosion was replaced, about the base of the mountains, by deposition. The best section of the Tertiary rocks[1] shows along the north face of the Beaver Divide, where the early Eocene (Wind River beds) are overlaid by the Bridger(?) and Uinta, and above an unconformity, by the Oligocene. These Tertiary rocks, largely shales and sandstones, are alluvial deposits laid down by streams from the higher central mountain area. The occurrence in the Beaver Divide Oligocene of a 100-foot gravel layer with bowlders of granite and other crystalline rocks up to a foot in diameter shows not only that there was considerable relief in the mountain region, but that any cover of sedimentaries had been cut through into the crystallines. How long after this the Oligocene deposit continued in the Wind River basin is not known, for the present top of the Oligocene cannot be shown to be the summit of the Tertiary series. Subsequent to Oligocene time came the erosion which ended in the production of the summit peneplain described below. From this point on, the history of the Wind River Mountains is to be read from the land forms and not from the sedimentary rocks.

THE SUMMIT PENEPLAIN

An accordance of summit levels in the central and northern part of the range is believed to be an inheritance from a peneplain which formerly extended throughout the range, and which in its highest

[1] Sinclair and Granger, *Eocene and Oligocene of the Wind River and Big Horn Basins*, Bull. Am. Mus. Nat. Hist., Vol. XXX, Fig. 2 A.

FIG. 1.—View north from Wind River Peak, showing sky line in central part of the range

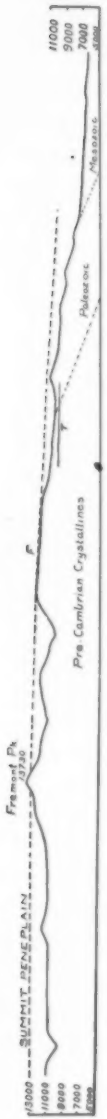

FIG. 2.—Profile across the Wind River Mountains through Fremont Peak. F, flat. T, valley terrace level

remnants now stands about 12,500 feet above sea-level. Looking north from Wind River Peak (Fig. 1) we see the sky line to be composed of rounded summits dropping to the east in an even line, but with occasional points rising sharply above this line. Further north, north and east of Fremont Peak and showing on the Fremont Peak quadrangle, extensive flat or gently rounded areas occur at heights of over 12,000 feet. Such are, the flat east of Indian Pass (Fig. 2, F), Horse Ridge, Goat Flat, the flat along the divide at the north end of the range, and several smaller flats west of the crest. The first two are not strictly level, but rolling, grassed, and rounded upland areas, their higher points rising somewhat above the general flat level.

The whole range was not reduced to the peneplain level. Fremont Peak and the higher points north along the range seem to rise distinctly above the general summit level, and the rate of rise of the ridges or flats which have been named would not carry them to the summit by several hundred feet. We may picture the condition at the close of this epoch as a plain rising along what is now the crest of the range to low rounded hills a few hundred feet in height.

This peneplain is not recognized in the southern part of the range, probably because destroyed by later erosion. From the middle of the range north it is increasingly represented, especially east of the crest. It is preserved only on the crystalline rocks, though the first high escarpment of Paleozoic rocks, the Bighorn limestone, seems to come nearly if not quite to this level. The projection of the plain farther from the crest carries it well above the other Paleozoic scarps. Why it has been more completely destroyed to the south and on the west of the crest, we cannot say.

The remnants of the plain fall into a low arch (Fig. 2), which slopes east from over 12,000 feet along the crest to above 10,000 feet in its last remnants on the edge of the crystallines and the bordering Bighorn limestone, and drops to the northwest along the axis of the range.

The date of the summit peneplain cannot be fixed, from the area studied, more closely than that it is later than the main folding of the range; for it does not extend beyond the Paleozoic rim to any point where later deposits rest upon it. Blackwelder[1] has described a peneplain in the Laramie region of southeastern Wyoming, which makes the summit of the Laramie Mountains at 9,000 feet and cuts the Medicine Bow range at 10,000, with the summits of the latter rising above it as monadnocks. This peneplain is considered to be of post-Eocene age. Rich[2] has described a peneplain in southwestern Wyoming, which had been developed probably by the end of Miocene, while Baker, in a paper read before the Cordilleran section of the Geological Society in 1911, describes the occurrence of a peneplain throughout southwestern Wyoming in the end of the Miocene. Umpleby[3] describes an old erosion surface in West Central Idaho which may prove to be a peneplain and which he considers to be of Eocene age. It is perhaps as much as the facts known at present warrant, to state that the Wind River Mountains had been reduced to a peneplain, except for a few low residuals along the present divide, by mid-Tertiary time.

THE PLAINS AT THE SOUTH END OF THE RANGE

Plain No. 4.—The oldest plain below the summit peneplain is best represented north of Atlantic City, in the summit accordance of a hilly area above which the southern end of the range rises abruptly (Figs. 3, 4, and 5). These summits stand at 8,500 feet farthest from the range, but rise to probably 9,000 feet at its base; and the original plain has been maturely dissected. East of Atlantic City, peaks of Paleozoic limestone rise to the level of this plain at 8,500 feet; and still further east the summit of Sheep

[1] *Journal of Geology*, XVII, 429.

[2] *Ibid.*, XVIII, 601.

[3] *Ibid.*, XX, 139.

Mountain reaches it at about 7,500 feet. The summit of Oregon Buttes, fifteen miles south of Atlantic City may be a remnant of the same plain. They are capped with Tertiary deposits.

This plain was not correlated with any plain-remnants along the range to the north, nor with any valley levels within the range. At the time of its formation, all of the region was reduced to a

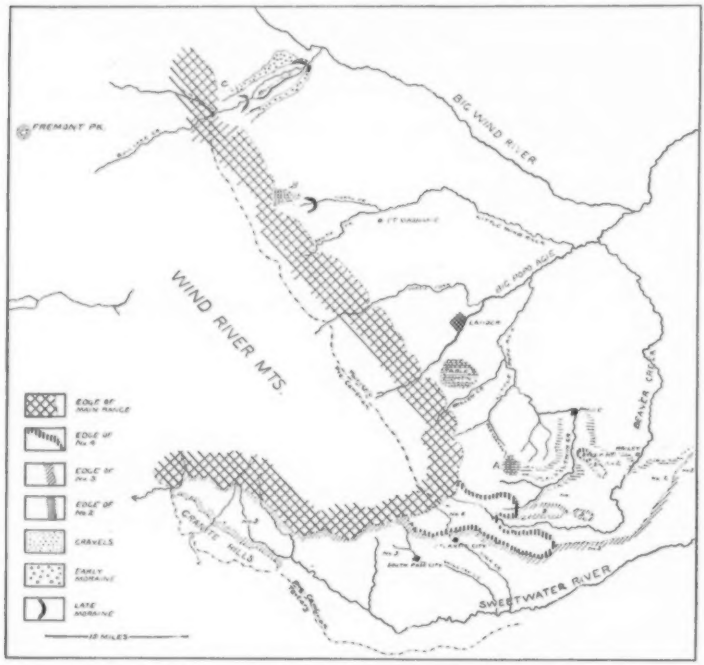

FIG. 3.—Map of the south end of the Wind River mountains, based on a map of Fremont County by N. H. Brown.

peneplain, except the Wind River Range, which rose, at the south, 4,000 feet above the plain level. The date of this plain is post-Oligocene, since it cuts rocks of this date along the Beaver Divide.

Plain No. 3. The Beaver Divide Plain.—Below No. 4 another plain (Figs. 3, 4, and 6) is widely developed about the south end of the Wind River Mountains, and to the east along the divide

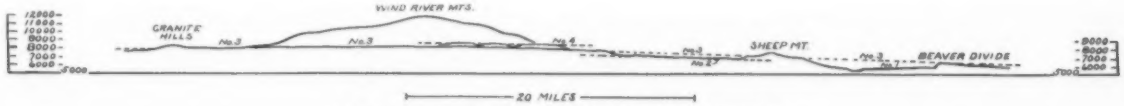

FIG. 4.—Profile of south end of Wind River Mountains

FIG. 5.—Plain No. 4 with the south end of the Wind River Mountains in the distance

between Beaver Creek, and the Sweetwater River. This is plain No. 3, or the Beaver Divide plain.

This plain is best shown west of Atlantic City and South Pass City, where it forms an even plain on the crystalline schists, above which monadnocks (Fig. 6), usually of granite, rise abruptly from a few score to one or two hundred feet. The plain, much cut away, continues west between the Granite Hills and the main range about the headwaters of the Sweetwater, where it cuts both the crystallines

FIG. 6.—View of plain No. 3 and monadnocks, west of South Pass City

and gravels which had earlier been deposited on an irregularly eroded granite surface. This same plain extends east from the south end of the range for over thirty miles along the divide between the Sweetwater River and Beaver Creek cutting in this area practically all the post-crystalline rocks of the region—the inclined Paleozoics and Mesozoics, and the horizontal and consolidated Tertiaries. In a few places residuals of each of these rocks rise above No. 3.

North from Atlantic City, where Nos. 3 and 4 meet, they differ

in level by some 400 feet. The cycle which produced No. 3 passed well beyond maturity, for the slopes joining 3 and 4 are gradual; and broadly opened valleys of No. 3 finger back into the area of No. 4. At the time of its completion the masses rising above its level were, besides the main range, the rolling hills which formed as a whole a dissected terrace at its south end, and occasional knobs along the Beaver Divide to the east.

Today the remnants of No. 3 have a distinct slope away from the range, amounting to about 1° around South Pass City. The plain stands at about 8,000 feet between the Granite Hills and the main range, about 8,000 to 8,200 feet by South Pass City (the higher value at the base of the mountains), 8,200 feet between Beaver Creek and Twin Creek near O'Meara's ranch, and 7,400 feet along the upper Beaver near Atlantic City. Along the Beaver Divide it drops to 6,770 feet ten miles east of Atlantic City, and to 6,600 east of Hailey (twenty-two miles northeast of Atlantic City). The Beaver today is flowing about 400 or 500 feet below the level of this plain.

The drainage on the Beaver Divide plain is unknown. Presumably it was radially away from the range. There is no evidence that the present arrangement of streams held at that time. The slope of the plain may or may not have been what it is today. There seems no way of deciding.

This plain carries gravels on its surface only where it cuts Tertiary rocks and where these rocks contain conglomeratic layers which furnish gravel to the plain.

Plain No. 2. Table Mountain Plain.[1]—Below the Beaver Divide plain, or No. 3, a later plain (Figs. 3 and 4) was very generally developed over the Mesozoic and later rocks of the Wind River region. During this stage the Beaver Divide came into existence and the Wind River and Sweetwater drainage areas became distinct. From this time on the geological history in these two main basins is somewhat different, and the topographical forms are unlike.

The condition of Plain No. 2 in the Sweetwater area is not

[1] Since No. 2 is provisionally correlated with the plain of Table Mountain, west of Lander, it is also called the Table Mountain Plain.

clearly known. On the upper tributaries of the Sweetwater, between the Granite Hills and the main range, No. 3 is postmaturely dissected by a system of valleys which are widely opened on the gravels and are narrower on the granites. This valley system may belong to No. 2. The Sweetwater cuts the crystallines south of the Granite Hills in a narrow valley which has doubtless been cut at a later date. Further east, at South Pass City and at Atlantic City, Willow and Rock Creeks are flowing in narrow valleys, cut below broad shallow valleys which are in turn cut below No. 3. South toward Oregon Buttes, and from the Beaver Divide toward the Sweetwater, the surface drops away to lower levels in such manner as to suggest very strongly that after No. 3 had been formed a later plain was developed to a very advanced stage throughout this part of the Sweetwater basin.

The best development of No. 2, however, is north of the Beaver Divide. Along the Beaver itself large remnants of this plain occur at 6,500 feet, 300 feet below No. 3 as developed on the divide. The only area which stands above No. 2, north of the Beaver and east of the mountains, is the higher part of Sheep Mountain. The plain is well shown along the north side of Beaver Divide as a broad bench sloping to the top of the cañon of the Beaver above Hailey. It forms the flat divide between Beaver and Twin Creeks and continuing from there north makes the high country about Bruce, and either just touches or rises slightly above the hills of folded Red Beds and Cretaceous which run northwest to beyond Lander.

At the south end of the range gravel occurs on No. 2 as scattered bowlders washed from near-by regions rather than as heavy deposits swept out from the central range. For example, in climbing from the Beaver where it bends to the north, to the Beaver Divide, one finds the hill-tops which come up to No. 2 carrying scattered bowlders of angular and subangular shape, frequently five or six inches and occasionally a foot in diameter, and derived from Paleozoic and crystalline rocks. But on the summit of the divide there is found a 100-foot layer of Tertiary conglomerate with bowlders quite like those occurring on the plain below. These bowlders on No. 2 are a thin veneer of local origin, derived from

the Tertiary, and are not to be confused with the Table Mountain gravels to be considered later.

Beyond the fact that the drainage was to the Wind River and the Sweetwater, little is known of the stream courses of the time. The Beaver may have flowed out, as today, south of Sheep Mountain, or, more probably, by a longitudinal stream north toward Lander.

PLAINS-REMNANTS ON THE EAST SIDE OF THE CENTRAL WIND RIVER MOUNTAINS

The Table Mountain Level, or No. 2.—None of the plains which have been described about the south end of the Wind River Range extend continuously north along the east side of the range. There are found, however, along the front of the range, isolated gravel-covered flats, at levels which correspond with those farther south. As careful study as conditions allowed makes it practically certain that these flats correspond to either No. 2 or No. 3 described above; probably to No. 2. The vertical distance between No. 2 and No. 3 is only 300 feet, and in many places No. 2 grades up into No. 3, so that the attempt to carry either plain north and to connect it with the gravel flats is difficult; especially in the absence of topographic maps and under the necessity of carrying the lines by eye from points of view some miles off the front of the range. Provisionally, however, these gravel flats, of which the best known is Table Mountain near Lander, are correlated with Plain No. 2, which has already been called the Table Mountain plain.

The southernmost of these flats is that which occurs (Fig. 3, A) where the Lander–Atlantic City road crosses from the headwaters of Twin Creek to Red Cañon Creek, a tributary of Little Popo-Agie River. Here a terrace (7,100 feet), cut on the Red Beds, is covered by a deposit of gravel to a thickness of 50 to 100 feet as shown on the north slope toward Red Cañon. The bowlders seen over the surface are commonly less than one foot in diameter though some reach a foot, and a few are somewhat larger, but down the north face of the terrace loose bowlders up to six feet in diameter are met with. The bowlders are Paleozoic and crystalline rocks of the foothills and main range, and must have come directly from the range as no Tertiary beds are in position to act as an intermediary

in furnishing the material to the present deposit. The deposit seems to be due to aggradation by the earlier Twin Creek.

A second gravel flat tops Table Mountain south of Lander, south of the Big Popo-Agie, at an elevation of 7,200 to 7,300 feet. A slide on the north side of the Mountain shows 175 feet of gravels resting on a somewhat uneven surface of Chugwater and later beds. In the section the bowlders usually reach a size of one to three feet, but many are over five feet and one was seen ten feet in diameter. The bowlders are well rounded, closely packed, and much weathered and consist of Paleozoics and crystallines. The filling between the bowlders is a sort of granitic sand, which seems to have come from the rotting of the bowlders. From a little distance the deposit appears to be indistinctly stratified. There is no evidence that it is not stream-made, though the size of the bowlders has been thought to indicate ice-action. The bowlders, however, are not larger than those found in arid regions at the head of alluvial fans some distance out from the mouth of the feeding cañons. The slope of Table Mountain is estimated at twenty-five feet per mile away from the mountain. The slope seems too gentle for the accumulation slope of such coarse materials, and the fact that the surface of Table Mountain is not a plain, but is trenched by shallow valleys indicates that it is not original but a cut surface. The Ten Sleep sandstone ridge to the west is cut away to a level corresponding to that of Table Mountain, as if a rather broad valley had here opened out from the range.

A similar deposit of coarse gravels forms a high flat near the range on the north side of the North Fork of Little Wind River (Fig. 3, B), at an elevation of from 7,445 to 7,700 feet. These gravels have a thickness, at the south end of the exposure, of 250 feet, and lie on the inclined Chugwater beds. They consist of well-rounded bowlders up to six feet in diameter, closely packed and thoroughly rotted. Stratification here is distinct and several layers of sand and fine gravel, up to four or five feet in thickness, occur in the deposit, showing that it is water-laid. The surface relations of the deposit are shown in Fig. 7, where *A–B* is the flat under consideration. Its surface is nearly level, and it is cut by *D–E*, a more irregular plain which drops away toward the Wind

River. The slope *A–B* is not an original plain, but was cut after the deposition of the gravels, and antedates the plain *D–E*, which cuts it.

The last terrace deposit of this kind studied is on the north side of Bull Lake Creek (Fig. 3, C), at an elevation of 7,400 feet. No section is shown here, but the deposit lies above and distinct from the moraine of the earlier glacier, which occupied Bull Lake Creek Valley. It is believed to be much earlier than either of the two glaciations of the region.

The meaning of the gravels.—These high level gravels are a largely unsolved problem to us, as are similar deposits to other workers in the Rocky Mountain region. If our correlation is

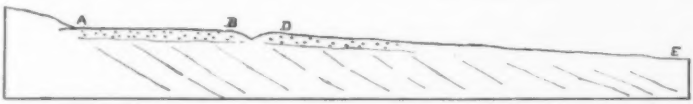

FIG. 7.—Diagram to show the relation of gravels on No. 2 (*A–B*) to the later plain (*D–E*).

correct, at some time after the up-arching of the summit peneplain which had been developed over the entire region, a peneplain was developed around the mountain on the Mesozoic and younger beds. This is plain No. 2. Low foothills of Paleozoic sandstone and limestone rose above this, and within this Paleozoic rim was the higher mass of the central crystalline area. At this time broad valleys ran back well to the crest of the range. Along Bull Lake Creek, six miles within the range, such flats were seen at 9,800 feet, and they can be seen fingering into the uplands and rising to them with not very steep slopes. This condition was followed by a period of piedmont aggradation, which resulted in the deposit of the gravels widely about the cañon mouths. This aggradation may have been the result of aridity, or of crustal movement. It was followed by the planation which produced the nearly level flats on Table Mountain, Little Wind River, and Bull Lake Creek, which have been described. Subsequent to this period of planation came the long period of terracing which produced No. 1 and lower plains.

Plain No. 1.—After the completion of No. 2, the streams again deepened their valleys and developed widely over the region a series of plains at a lower level. Along the Beaver north from Hailey a flat was formed 8 to 10 miles in width, sloping with the stream and toward the stream from either side. Near the Beaver the remnants now stand 200 feet above the stream. Above the lower Beaver cañon, a little up stream from Hailey, this plain is not shown; nor is it recognized along the Sweetwater.

The valley divide which crosses north of Twin Creek from the main range foothills to Sheep Mountain, is a remnant of No. 2, but from here north the divides between the streams which cross the valley belong to No. 1. On the Little Popo Agie–Willow Creek divide the elevation is 5,575 feet, north of Willow Creek 5,450 feet, and south of Lander 5,480 feet. The remnants of this plain slope from either side toward the axis of the longitudinal valley, indicating that the stream which controlled its formation was a longitudinal stream flowing northwest toward Lander, and that the valley was not drained as it is today, by transverse streams.

North from Lander, between the Popo-Agie and its north fork, a terrace runs far out into the valley and at Milford stands at 5,800 feet. North from this point a series of terraces occurs, below the Table Mountain levels, the highest of which are referred to level No. 1. These terraces stand at 5,730 feet between North Fork and Mill Creek, and at 5,940 feet near the road, north of the North Fork of Little Wind River. The levels rise toward the northwest, along the Wind River, and also toward the mountains.

The cutting of No. 1 was the inauguration of a period of terrace cutting which has continued to the present. New plains have been made by the swinging and deepening streams at successive lower levels, but since this terrace period has been different in the different stream basins, and since in any one basin the terraces run into each other, it was found impossible, in the absence of topographic maps, to study it in any detail. Between the North Fork of the Big Popo-Agie and the Little Wind River these lower terraces often carry large bowlders, up to 3 feet and over in diameter, which seem to have been derived from the erosion of the coarse gravels on plain No. 2, since largely destroyed.

Along the Beaver north from Hailey, No. 1 has been well dissected. During this later terracing Little Popo and Willow Creek have cut back and captured the streams which during the cutting of No. 1 had flowed northwest to Lander. In some cases there has been a recent silting-up of valleys, into which filling the present streams are again cutting. This is the case along the lower Beaver, the Wind River, and Sage Creek. The Little Wind River and the Big Popo are flowing on broad flats, and if silting has been going on they have not commenced to cut again.

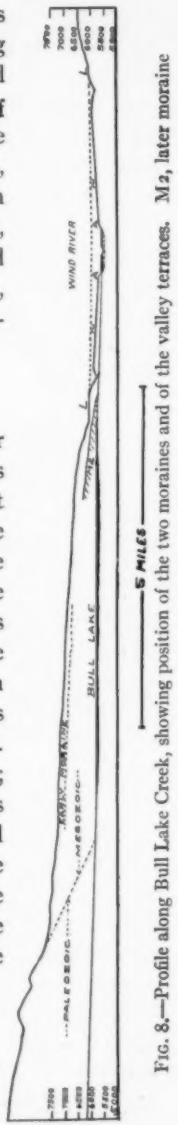

FIG. 8.—Profile along Bull Lake Creek, showing position of the two moraines and of the valley terraces. M_2, later moraine

GLACIAL HISTORY

The Wind River Mountains support a dozen or more small glaciers, and the summit region shows quite generally an Alpine topography, as a result of cirque growth (Fig. 1). In Pleistocene time glaciers occupied the main valleys, and in some cases extended a number of miles out onto the plains at the base of the range. Glacial features are considered in this paper only for the purpose of dating the terracing which has already been described, and for this purpose the conditions about Bull Lake Creek can best be used (Fig. 8).

Moraines of an earlier and a later period occur; and in each case the ice advanced about ten miles from the foot of the range, almost to the Wind River. The moraines of the later glaciation make concentric ridges about the lower end of Bull Lake and connect with gravel outwash which floors the inner valley (Fig. 8, *A–A*) of Wind River. Since their deposition they have been cut somewhat where Bull Lake Creek passes through them, and along Wind River ten feet of silt has been deposited above the outwash gravels (the river is now cutting into silt and gravels); but in all

except small details the region has remained otherwise unchanged; so that at the time of the last glacial advance it was essentially as it is today.

The later moraines occur in close association with the present valley of Bull Lake Creek, either as terminal moraines below Bull Lake, or as small recessional moraines up valley. The earlier moraine, however, shows (Fig. 9) a very different relation to the present valley. At the base of the mountains it is 100 to 200 feet thick, with a typical morainic topography, and its mass of bowlders lies on inclined Mesozoic rocks several hundred feet above the floor of the valley. It was laid down in reference to a much shallower valley (probable restoration shown in Fig. 9), and the extension of the drift to the north suggests that near the Wind River

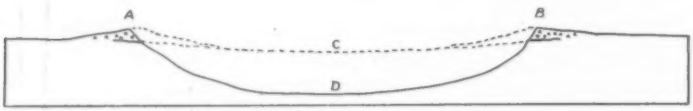

FIG. 9.—Section (diagrammatic) to show the position of the early moraine to the earlier (ABC) and present valley (ABD) of Bull Lake Creek.

the present stream departs from the course of the earlier stream. The cutting of the present Bull Lake Creek, to a depth near the mountain of some 800 feet, is the work of interglacial time.

The earlier drift is known to be older also because of its more weathered and eroded character, and because of its relations to certain terraces. The earlier moraine rests upon a terrace fragment (Fig. 8, L). Fragments of this terrace are found at a corresponding level across the Wind River. This terrace rises toward the range and is overridden by the moraine. It is therefore preearly glacial. The valley *A–A* existed before the last glacial time, since the outwash gravels of the last ice advance run into it. The cutting of the broad valley below the restored *L–L*, which is floored by the terrace *N–N*, is also the work of interglacial time, and was done at the same time that Bull Lake Creek was deepening its earlier valley. The broad terrace *L–L*, reaching back toward the range, is one of the later terraces of the Wind River region, either No. 1 or later, but it was cut before the earlier glaciation. It

follows that the long period of terracing which has been described, in which plains 4, 3, 2, and 1 were successively formed, is all to be placed before the time of the earlier glaciation. It may be that there were still earlier glaciations in the Wind River Range but if there were they have not been recognized, and for the present practically all of the higher terraces may be assigned to the Tertiary.

VARIATIONS OF CERTAIN ADIRONDACK BASIC INTRUSIVES[1]

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INTRODUCTION

The basic intrusives—gabbros and diabases—discussed in this paper are wholly confined to the North Creek (Warren Co.) New York quadrangle, a detailed geologic map of which will soon appear as a publication of the New York State Museum. The region, though well within the Adirondack area, has afforded an unusual opportunity for detailed field work because of the numerous roads and trails and the large number of excellent exposures as compared with the Adirondacks in general. The gabbros occur almost always as small stocks or bosses, while the diabase always occurs as true dikes. In all, 61 gabbro masses and 11 diabase dikes have been mapped within the quadrangle. Among the gabbros there are many remarkable variations of primary and secondary origin. It is the chief purpose of this paper to describe and attempt to explain the primary variations, though certain secondary features will also be briefly discussed. The writer is greatly indebted to Professors J. F. Kemp, H. P. Cushing, and C. H. Smyth for their able papers dealing with Adirondack basic intrusives, but, so far as the writer is aware, little or no attention has been given to an explanation of the primary variations of the gabbro.

ROCKS OF THE REGION

The rocks of the North Creek quadrangle are all of pre-Cambrian age, and these given in their relative order of ages comprise the Grenville sedimentary series of various gneisses, quartzite, and crystalline limestone; syenite and granite; gabbro; pegmatite; and diabase.

The Grenville strata are all highly metamorphosed, with limestone unusually prominent in this portion of the Adirondacks.

[1] Published by permission of Dr. J. M. Clarke, State Geologist of New York.

The syenite and granite break through the Grenville in batholithic masses of greater or lesser extent. These rocks, which are always foliated, vary from basic syenite through quartz syenite and granite to granite porphyry, and all are differentiation products from the same great cooling magma. About two-thirds of the area of the quadrangle is occupied by these rocks. Sometimes they are so closely involved with the Grenville as to preclude the possibility of separate mapping.

The gabbro, which exists under many facies, is clearly intrusive into the Grenville and syenite-granite series. It is generally more or less metamorphosed, especially along its borders where amphibolite is often developed. It occurs in numerous small masses.

Pegmatite dikes show a very close association with the gabbro, it being quite the rule to find such coarse grained dikes often of very respectable size cutting the gabbros and frequently sending small tongues into the latter rock.

Diabase occurs in small dikes, and in contrast with the gabbro, it is remarkably uniform in texture and composition. The writer has observed the diabase cutting the pegmatites and, in one case, the gabbro.

The accompanying geologic map gives a fair idea of the relations of the various rocks of the region under discussion.

THE GABBRO AND ITS DERIVATIVES

MODE OF OCCURRENCE

The gabbro and its derivatives nearly always occur in the form of small stocks or bosses rather than as true dikes, the length ranging from 30 or 40 feet to about a mile, and with widths up to $\frac{3}{4}$ of a mile. The ground plan as represented on the geological map is almost invariably elliptical, though sometimes approaching the circular. When the contact with the country rock is carefully traced out it is commonly found to be sharp and shows smooth or flowing outlines against the country rock. These features are pretty well shown on the accompanying map.

In only two or three cases do the gabbro masses approach the true dike-like form, and in each of these fine grained tongues were found to extend into the surrounding rock. A good example is

the stock or dike 1⅓ miles southeast of Chestertown which has several such tongues, one of them from 1 to 6 inches wide clearly cutting the granite porphyry for 30 feet. However, it is a striking fact, that, in spite of many excellent contacts which were

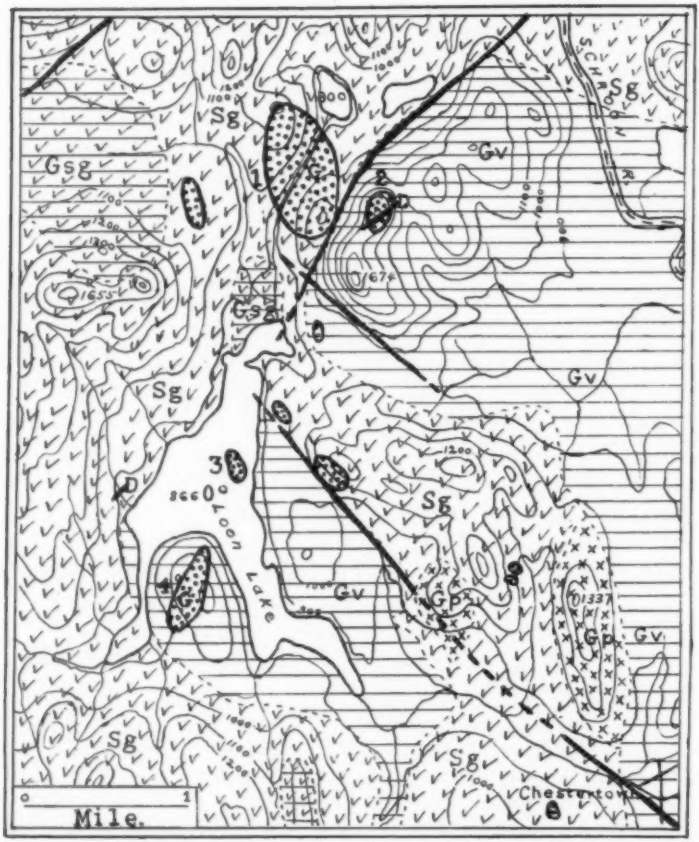

FIG. 1.—Geologic map of part of the North Creek, New York, quadrangle, showing the relation of the gabbro stocks to the other pre-Cambrian rocks.

Gv. = Grenville series; Sg. = Syenite and granite gneisses; Gsg. = Grenville-syenite-granite mixed gneisses; G. = Gabbro; and D. = Diabase. Heavy black lines = faults. Contour interval = 100 feet.

observed, such dike tongues are so rare. As Harker says:[1] "Although most of the bodies of granite and other plutonic rocks which have been loosely described as bosses, and so rendered in ideal sections, are doubtless of laccolithic or other stratiform shape; some, not of the largest dimensions, appear to have a plug-like form, with more or less vertical boundaries." The North Creek bosses are certainly of this plug-like or pipe-like form as shown by the very character of their eroded cross-sections and also by the vertical contacts with the country rock. Among the many fine contacts which came under the writer's observation, not a single exception to the rule of vertical or practically vertical contacts was noted.

In most cases the long axes of the stocks lie parallel to the foliation of the inclosing rock, though there are some notable exceptions. It would therefore seem that the molten intrusives generally followed the lines of least resistance but, even in these cases, the broad ends of the stocks cut sharply across the foliation bands, sometimes for a distance of several hundred yards. Such a phenomenon is well exhibited at the south end of the large stock (see accompanying map) where a big quarry has been opened up along the contact.

The gabbro stocks are not at all uniformly distributed over the area of the quadrangle, the largest number being confined to a nearly north-south belt with a width of from 3 to 5 miles and extending through the middle of the quadrangle. This belt roughly corresponds to the general strike of the foliation. A secondary belt, about 1 mile wide and 5 miles long near the middle eastern boundary of the sheet, contains a dozen small stocks. With a single small exception the whole western side of the quadrangle is devoid of gabbro masses. In the northeastern portion a few stocks occur, but they may really belong to some other belt not yet mapped. Thus we see that the gabbro intrusions were limited to pretty well defined areas or belts.

Among these gabbro stocks four types of occurrence are especially noteworthy as follows: (1) the normal, dark, basic gabbro with diabasic texture, and usually homogeneous throughout;

[1] *Natural History of Igneous Rocks* (1909), p. 86.

(2) gabbro chiefly of the normal type but with irregular patches or masses of lighter colored rocks of syenitic or dioritic make-up, these patches blending with the normal gabbro; (3) the whole stock made up of lighter colored, more acidic rock; and (4) any one of the above types with blocks or inclusions of the country rock. These four types are all primary variations. Examples of the last three types will be given later.

MEGASCOPIC FEATURES

The gabbro and its derivatives present a truly remarkable number of facies or varieties clearly visible to the naked eye and these will now be briefly described.

The coarseness of grain varies from the merest fraction of a millimeter to fully an inch (e.g., stock No. 4 of accompanying map). The fine grained portions are confined to the borders of the stocks or the few branching tongues, and were caused by the more rapid chilling of the rock in those positions. However, even the finest grained rocks are holocrystalline. As a rule the coarseness of grain increases toward the interior of the masses, though often medium to coarse grained rocks extend to the very contact. The typical or prevailing gabbro shows a medium grain; that is, the grains are from 1 to 5 mm. across.

The texture varies from coarse to medium to fine grained granitoid, to medium to coarse grained diabasic (ophitic). The gabbro from stock No. 4 is an excellent example of diabase texture in which the feldspar laths attain a length of an inch or more. The typical gabbro always exhibits the diabasic texture.

In color the gabbro and its derivatives range from nearly black through dark to light gray, the darker varieties, in many cases, showing a slight reddish tinge due to the presence of garnets. The gray rocks all belong to the more acidic—dioritic and syenitic—facies below described. In one case a greenish-gray color was noted. The very dark color of the typical gabbro is due to the fact that the feldspars are so charged with tiny black inclusions.

In the typical gabbros the minerals commonly recognizable with the naked eye or hand lens are plagioclase, pyroxene, horn-

blende, garnet, biotite, and ilmenite, while in addition to these orthoclase and quartz may often be seen in the more acidic phases.

Except for the pretty common presence of highly gneissoid to even schistose amphibolite borders, the stocks of typical gabbro are practically devoid of gneissoid structure. Some of the lighter colored, more acidic phases, however, show fairly well developed foliation.

It is important to note that many of the above described variations may be found within a single stock as, e.g., No. 1. The following statements from Smyth's description[1] of a similar western Adirondack gabbro fittingly apply here:

> These (primary) changes in character take place very suddenly, and the different phases are most irregularly distributed, seeming to conform to no law. . . . . These primary variations in the rock suffice to give considerable diversity to different portions within a limited area, but this diversity is greatly intensified by certain secondary modifications of structure and composition. As a result of the combined effect of primary and secondary variations, it would be easy to collect, within an area of a few square rods, a half dozen or more specimens whose appearance even in thin-section would scarcely suggest that they had any connection with one another.

Cushing says[2] of the Adirondack gabbros in general that they show much variation, both primary and secondary, from place to place. Both of these investigators proceed to discuss the secondary variations and their causes but, so far as the writer is aware, little or no attention has been given to the causes of the primary variations, which is the chief object of this paper.

MICROSCOPIC FEATURES

Mineralogical composition.—The following table will serve to show the great range in mineralogical composition of the gabbro and its derivatives. The figures refer to percentages by volume and are meant to be close approximations only.

Perhaps the most striking feature brought out by this table is the range of rock types, through many intermediate phases, from a very basic olivine norite to quartz-hornblende syenite. Thus, No. 1 is an olivine norite; Nos. 2, 3, 4, 6, 7, and 9 are

[1] *Amer. Jour. Sci.* (April, 1896), pp. 273–74.

[2] *N.Y. State Mus. Bull.*, 95, p. 328.

TABLE I

MINERALOGICAL COMPOSITION OF THE GABBRO AND ITS DERIVATIVES

	Slide No.	Ortho-clase	Plagio-clase	Horn-blende	Hyper-sthene	Augite	Dial-lage	Ilmenite	Pyrite	Biotite	Garnet	Quartz	Zoisite	Zircon	Apatite	Olivine	Titanite
1.....	45	..	50 Lab.	..	15	..	..	3	..	9	8	..	..	..	..	15	..
2.....	6	..	50 Lab.	8	17	..	7	1	little	8	8	..	..	..	..	..	..
3.....	2	4.5	38 Ol.-Lab.	27	12.5	3	..	2.5	1	7	3.5	..	..	..	little	..	..
4.....	46	15	30 Lab.	10	15	..	..	5	..	5	20	..	..	..	..	..	..
5.....	42	10	40 Ol.-Lab.	25	..	..	23	little	little	1	little	..	..	..	..	..	..
6.....	47	10	30 Ol.-Lab.	25	20	..	10	1	..	2	2	..	..	..	..	..	..
7.....	1	5	40 Ol.-Lab.	16	25	..	..	1	..	5	8	..	..	..	..	..	..
8.....	60	20	40 Ol.-Lab.	10	14	..	..	1	1	2	10	1	1	..	..	..	..
9.....	5	5	45 Ol.-Lab.	14	20	..	..	2	1	6	2	..	..	..	..	..	..
10.....	49	32	10 Ol.-And.	45	..	..	..	2	little	6	5	..	..	little	..	..	..
11.....	3	32	20 Ol.-Lab.	25	..	..	..	5	..	5	..	10	1	..	little	..	little
12.....	4	15	57 Ol.-Lab.	15	..	..	..	2	1	10	..	..	..	little	..	..	..
13.....	44	50	15 Ol.-And.	20	..	8	2	little	little	..	1	2	..	little	little	..	..
14.....	43	45	15	28	..	2	..	1	little	..	..	.8	..	..	little	..	..

hornblende norites; No. 5 is a hornblende gabbro; No. 8 is a gabbro-diorite; Nos. 10, 13, and 14 are hornblende syenites; No. 11 is a monzonite; and No. 12 is a diorite. The large number of minerals—16 in all—is also notable. Also it is important to note that, in the above table, Nos. 3 and 4, 7 and 8, 9 and 10, and 11 and 12, respectively, come from single stocks.

The predominating mineral is feldspar, which ranges from labradorite alone in some rocks through all stages, to those rocks which are rich in the more acid plagioclases or orthoclase.

Hornblende, generally in considerable amount, occurs in all but one (No. 1) of the rocks. Sometimes it makes up a fourth or more of the whole rock. Much of the hornblende in the more basic rocks, at least, is of secondary origin and forms corrosion rims (below described) around other minerals. Its color varies from green to brown. In one slide many examples of the transition from pyroxene to hornblende are perfectly shown.

Hypersthene, with a single exception (No. 5), is an important constituent of all the more basic types. It is almost always highly granulated and with pleochroism from greenish-gray to pale reddish-brown.

Augite and diallage of greenish-gray color, and with good cleavage, are only occasionally present and rarely as important constituents.

Ilmenite is invariably present in amounts up to 5 per cent, and often shows transition to leucoxene.

Pyrite in small amount seldom fails.

Biotite and garnet of the usual sort, though mostly in tiny flakes or grains, are present in moderate quantity in all but certain of the more acidic facies. The unusually high percentage of garnet in No. 4 is a fine grained border phase of a stock.

Quartz, in small irregular shaped grains, is wholly confined to the acidic types.

Zoisite, in small stout prisms, sometimes makes up about 1 per cent of the rock.

Zircon and apatite, in very small quantities, are wholly confined to the acidic facies. The absence of the apatite from the typical gabbros is especially noteworthy.

Olivine was noted in but one case (No. 1) and this in the only rock from which hornblende is missing.

Titanite in a few small grains was noted in No. 11.

Reaction or corrosion rims.—Reaction or corrosion rims, which are well known in many basic rocks, are exhibited in a truly remarkable manner in the North Creek region gabbros. In the examples most often described, the core is olivine, but in the gabbros here considered the writer has observed cores of olivine, hypersthene, magnetite, augite, and diallage with from one to five distinct, successive rims surrounding the cores. Professor Kemp has described[1] and figured a number of interesting examples of reaction rims observed in certain gabbros of the eastern Adirondacks.

The following nine types of reaction rims comprise most of those noted by the writer in the North Creek gabbros:

1. Ilmenite surrounded by hornblende.
2. Diallage surrounded by hornblende.
3. Augite surrounded by hornblende.
4. Hypersthene surrounded by garnet.
5. Hypersthene surrounded by successive zones of biotite and hornblende.
6. Olivine with successive zones of hypersthene, hornblende, and garnet.
7. Olivine with successive zones of hypersthene, biotite, and garnet.
8. Hypersthene with successive zones of biotite, feldspar, and garnet.
9. Ilmenite with successive zones of biotite, hornblende, garnet, and biotite.

In nearly all cases the material immediately inclosing the rims is feldspar which, in a sense, adds another zone to each of the above. No. 6 is like one of those described by Kemp. No. 9 is a remarkable example and, because of its additional outer rim of biotite, is even more interesting than a case described by Lacroix.[2] Some of the others may be new examples. The material of each rim appears to be highly granulated or at least made up of numerous small grains. It seems certain that where hypersthene

[1] *Geol. Soc. Amer. Bull.*, V (1894), 218–21.

[2] *Bull. Soc. Min. Fr.*, XII (1889), 232.

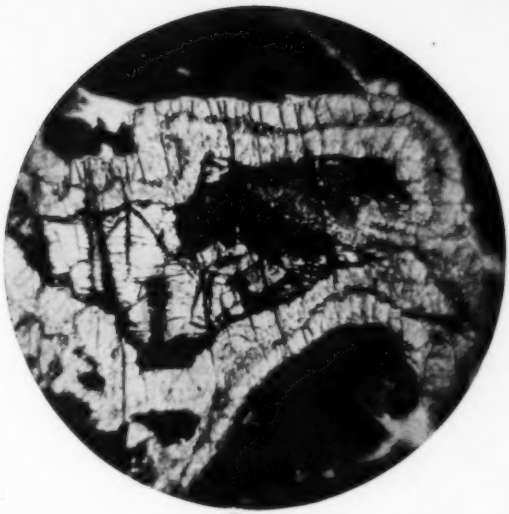

FIG. 2

FIG. 3

FIGS. 2. and 3.—Photomicrographs of thin-sections of gabbro from stock No. 4 (see accompanying map). Each magnified 15 diameters.

In the upper figure the large central mineral is olivine completely surrounded by successive rims of hypersthene, biotite (narrow and dark), and garnet. Surrounding all are broad laths of labradorite.

In the lower figure the large, black, central mineral is ilmenite followed by successive rims of biotite, hornblende, garnet, and biotite. The second and third—biotite and hornblende—rims are not separable in the photograph. Surrounding all are labradorite crystals.

envelopes olivine, the former has secondarily developed from the latter. The olivine cores are of very irregular shapes and in all sizes. Where hypersthene forms the core it is probable that all of the original olivine has been altered to hypersthene. The common occurrence of hornblende rims around pyroxene strongly suggests the derivation of the former from the latter. Garnet is almost invariably in contact with feldspar, which suggests the partial formation, at least, of the garnet from the feldspar.

CHEMICAL COMPOSITION, NORM, AND MODE

Excellent exposures of what is regarded as very typical gabbro occur in the railroad cut $1\frac{1}{4}$ miles south of The Glen. This rock has been chemically analyzed for the writer by Professor E. W. Morley. The following table shows the chemical composition, norm, and mode, the last having been determined from thin-sections.

TABLE II

Chem. Comp.		Norm		Mode	
SiO_2	46.40	Orth	6.67	Plagioclase	32.72
Al_2O_3	14.17	Alb	22.53	Orthoclase	3.77
Fe_2O_3	2.03	Anor	23.35	Hornblende	27.92
FeO	13.12	NaCl	.82	Hypersthene	14.30
MgO	4.94	Ilm	5.78	Biotite	7.09
CaO	9.65	Mag	3.02	Augite	3.29
Na_2O	3.14	Pyr	.24	Garnet	4.30
K_2O	1.12	Apat	2.02	Ilmenite	4.17
H_2O+	.02	Diop	17.53	Pyrite	2.08
H_2O-	.25	Hyper	8.02	Apatite	.36
TiO_2	3.03	Oliv	9.32		
P_2O_5	.80	H_2O+ZrO_2	.32		
Cl	.15				
MnO	.44				
S	.14				
BaO	.18				
SrO	.10				
F	.04				
ZrO_2	.05				
Total	99.77				

Class III	Order 5	Rang 3	Subrang 4
Salfemane	Gallare	Camptonase	Camptonose

Under the old qualitative system the rock is a hornblende norite, while according to the quantitative system it is a hornblende-camptonose.

In thin-section the plagioclase is seen to range from oligoclase to labradorite, and the analysis and mode show that the average composition is that of a basic andesine.

The high TiO_2 of the analysis shows either ilmenite or very titaniferous magnetite, the ilmenite being far more probable because of the difficulty of otherwise accounting for such a low content of Fe_2O_3.

THE DIABASE

MODE OF OCCURRENCE AND DISTRIBUTION

In striking contrast with the neighboring gabbro, the diabase invariably occurs in typical dikes which have clearly broken through narrow fissures in the country rock. They vary in length from 20 or 30 feet to 200 yards, and in width from $5\frac{1}{2}$ inches to 40 feet.

The chief features of occurrence are brought out in the following description of the largest dike of the region which lies at the western base of Heath Mountain or 3 miles west-northwest of Warrensburg. This dike has a maximum width of 40 feet and a length of 200 yards. It is fine to medium grained toward the interior and very fine grained along the borders. It breaks through both Grenville and granite gneisses and the contacts are everywhere perfectly sharp, there being no evidence whatever of contact metamorphism. A number of small tongues, from one inch to three or four feet wide, branch off the large dike and extend as much as 25 or 30 feet into the country rock. One of these branches cuts a pegmatite dike and another cuts Grenville limestone. This large dike strikes across the foliation almost at right angles.

One and one-half miles southeast of Johnsburg a diabase dike, $2\frac{1}{2}$ feet wide and 60 feet long, cuts Grenville quartzite parallel to the foliation. All of this rock is fine grained but exceptionally so at the contacts, and on one side an inch wide zone of basaltic glass or obsidian is perfectly developed with some very small tongues of glass extending into the country rock.

Cutting gabbro stock No. 2 (accompanying map) there is a typical diabase dike 4 feet wide, with fine grained borders, and with very sharp contacts against the gabbro.

In all 11 diabase dikes were found, these being well scattered over the quadrangle. Most of them cut across the foliation of the country rock at high angles, thus differing from the gabbros, and they probably have been forced up along joint planes. In 9 of the 11 occurrences the dikes strike northeast and southwest which is quite the rule for such dikes in the eastern Adirondacks. So far as can be determined, these dikes all come up vertically through the country rock.

MEGASCOPIC AND MICROSCOPIC FEATURES

The diabase is a very dark bluish-gray to almost black rock which, in all exposures, is hard and fresh except for the immediate surface which is often weathered to reddish-brown.

The granularity and texture vary from glassy to very fine grained to medium grained diabasic, the finer grained rock being wholly confined to the borders and the diabasic texture nearly always being just visible to the naked eye in the typical medium grained rock. Except for the above named differences the diabase shows no facies whatever visible to the naked eye, and this again is in marked contrast with the gabbros.

The diabase is wholly devoid of any metamorphism and inclusions of country rock are never found. The only minerals recognizable by the naked eye are the tiny feldspar laths and an occasional pyrite speck.

The whole range in mineralogical composition is brought out in the following table. The figures refer to percentages by volume and are meant to be close approximations only.

The remarkable similarity in composition and the small number of minerals represented stand out in marked contrast against the gabbro and its facies. Nos. 1, 2, and 3 are typical holocrystalline diabases from widely separated dikes. Nos. 4 and 5 represent finer grained or border phases and have more or less glassy groundmass. No. 5 presents a striking appearance under the microscope because the feldspar crystals which are incipient and almost indeterminate tend toward sheaf-like bundles.

No. 1 of Table III, which may be regarded as typical of all the diabases, is from the large dike (above described) at the base of Heath Mountain. The fine to medium grained rock shows an

excellent diabasic texture visible even to the naked eye. Judging by the extinction angles, the broad laths of somewhat decomposed plagioclase range from andesine to labradorite in composition. Pale reddish-brown augite, in stout prisms, shows a very faint pleochroism. It exhibits good cleavage and sometimes good crystal boundaries. The biotite is much changed to chlorite and stained with black iron oxide. The magnetite often shows transition to leucoxene. Apatite occurs in tiny needles, and pyrite and quartz in small irregular grains, the latter probably being of secondary origin.

TABLE III

MINERALOGICAL COMPOSITION OF THE DIABASE

	Slide No.	Andesine to Labradorite	Augite	Biotite	Ilmenite	Pyrite	Glassy Groundmass	Quartz	Apatite
1	8	47	25	22.5	4	½	..	little	little
2	48	55	37 mostly chlorite		6	little	..	2	little
3	7	55	40 mostly chlorite		5	..	..	little	little
4	10	5	5	..	many specks	..	85	..	..
5	9	55	14	..	5	little	25	1	..

CHEMICAL COMPOSITION, NORM, AND MODE

The diabase from the dike at the western base of Heath Mountain has been chemically analyzed for the writer by Professor E. W. Morley. The following table (p. 174) shows the chemical composition, norm, and mode, the last having been determined from thin-sections.

Thus, according to the old qualitative classification, the rock is a biotite-diabase, while under the new quantitative chemical classification it is a biotite-camptonose.

The amounts of SiO_2, Al_2O_3, and CaO in the analysis strongly bear out the determination of the plagioclase as ranging from andesine to labradorite.

Such a high content of FeO in the analysis makes it certain that the biotite is rich in ferrous iron, since there is not enough ilmenite and augite to account for so much FeO.

The sulphur appears too low in the analysis as judged by the amount of pyrite visible even to the naked eye.

The high TiO_2 shows either ilmenite or that the magnetite is decidedly titaniferous (most likely the former), though a little of the TiO_2 may be in the biotite.

TABLE IV

Chem. Comp.		Norm		Mode	
SiO_2	50.57	Qtz	2.04	Plagioclase	40.78
Al_2O_3	13.58	Orth	11.12	Augite	27.20
Fe_2O_3	3.26	Alb	24.10	Biotite	23.59
FeO	10.09	Anor	18.63	Ilmenite	6.56
MgO	4.98	NaCl	.12	Pyrite	1.13
CaO	7.67	Mag	4.64	Quartz	.52
Na_2O	2.92	Ilm	5.02	Apatite	.19
K_2O	1.89	Apat	.67		
H_2O+	.16	Fluor	.16		
H_2O-	.94	Diop	14.44		
TiO_2	2.68	Hyper	17.41		
P_2O_5	.28	H_2O+S	1.13		
Cl	.09				
F	.09				
MnO	.36	Class III	Order 5	Rang 3	Subrang
BaO	.09	Salfemane	Gallare	Camptonase	Camptonose
SrO	.10				
S	.03				
Total	99.78				

It is important to note that the typical gabbro and diabase are almost exactly the same in chemical composition (both being camptonose) except for somewhat higher silica and lower lime in the diabase, this difference probably being due to the slightly more acid character of the plagioclase in the diabase. Thus, these two rocks have quite certainly been derived from the same basic source of supply, though at different times.

CAUSE OF THE PRIMARY VARIATIONS OF THE GABBRO

APPLICATION OF DALY'S MAGMATIC STOPING HYPOTHESIS

What has caused the remarkable primary variations of the gabbros? The writer believes there is strong evidence favoring the application, to a greater or lesser extent, of Daly's magmatic stoping and assimilation hypothesis to the solution of this problem.

It is the present purpose to state only the fundamental principles of this hypothesis, the reader being referred to Daly's original papers[1] for details. The essential points, according to Daly, are:

1. "Each acid, batholithic magma has reached its present position in the earth's crust largely through the successive engulfment of blocks broken out of the roof and walls of the batholith."

2. "The sunken blocks must be dissolved in the depths of the original fluid, magmatic body, with the formation of a 'syntectic,' secondary magma."

3. The period of most active intrusion, accompanied by stoping and abyssal assimilation, is when the magma is thoroughly molten.

4. When the magma or stock becomes very viscous, the blocks (xenoliths) will neither sink nor become assimilated.

In all of Daly's papers it would seem that his hypothesis is generally meant to account for only large and more acidic intrusive bodies than the gabbro stocks here considered. However, there appears to be no reason why the essential principles of the hypothesis should not be applicable to these smaller and generally more basic stocks.

It should be distinctly understood that the writer does not believe Daly's hypothesis to involve the only processes to account for the type of occurrence and primary variations of these gabbro stocks, but rather the observed facts warrant his belief that magmatic stoping and assimilation have been important processes. Other processes, such as marginal assimilation, or in the cases of certain smaller and more dike-like masses, simple pushing aside (displacement) of the country rock, may well enough have operated.

SIGNIFICANCE OF THE MODE OF OCCURRENCE

We have shown that the gabbro stocks are of the plug-like or pipe-like form with practically vertical boundaries. Now, as Harker says:[2]

> An intrusive working its way up through solid rocks by "overhead stoping" must if this action be sufficiently continued, acquire something of the vertical

[1] *Amer. Jour. Sci.*, XV (1903), 269–98; *ibid.*, XVI (1903), 107–26; *ibid.*, XXVI (1908), 17–50.

[2] *Natural History of Igneous Rocks*, p. 86.

cylindrical form which seems to be implied in the term boss (or stock). . . . . The space which they (bosses or stocks) occupy can scarcely have been provided by the thrusting aside of the contiguous rocks, assisted by some contraction of the latter in metamorphism. They appear, as Barrois says of the granite of Rostrenan in Brittany, to have penetrated the solid rocks by cutting a way through them like a punch, not by thrusting them aside like a wedge. In such cases we may suppose that "stoping" has played an important part.

Daly, speaking of granite stocks and batholiths, says:[1]

Most, if not all, of these bodies in their accessible portions have replaced nearly equivalent volumes of their respective country rocks. They are generally cross-cutting bodies. . . . . Where erosion has been profound, the ground plan section of the typical stock or batholith is seen to be elliptical. . . . . Both in ground plan and in vertical sections the contact surface is relatively smooth. Apophysal offshoots do interrupt the wall-rock, but the main contact lines as mapped on ordinary geological maps are characteristically flowing lines. Large scale, angular projections of country rock into well uncovered batholith are comparatively rare. Such smoothness of main contact surfaces is that which is to be expected on the stoping hypothesis.

These statements by Harker and Daly are precisely descriptive of the mode of occurrence of the typical basic stocks of the North Creek region. Stock No. 1 (see map) already described is a fine example. This rock was certainly not intruded by displacing or simply pushing aside the country rock, but rather it was a process of replacement. Thus the mode of occurrence of the North Creek stocks furnishes strong evidence in favor of magmatic stoping as an important factor in the intrusive process.

SIGNIFICANCE OF THE INCLUSIONS

A good proportion of the stocks contain inclusions of country rock. Among many examples are the following: $1\frac{1}{4}$ miles north-northeast of The Glen; 1 mile south-southeast of The Glen; $1\frac{1}{3}$ miles south of South Horicon; and $1\frac{1}{3}$ miles northeast of Pottersville. These inclusions, which are seldom more than a few feet long, are usually angular and irregularly arranged in the matrix. It is quite the rule that the dark colored minerals of the gabbro are arranged with long axes parallel to the long axes of the inclusions, this probably having been due to a sort of flow structure

[1] *Amer. Jour. Sci.*, XXVI (1908), 20.

which was developed around the inclusions during their movement through the magma and just before its solidification. The very presence of the inclusions or xenoliths proves that the process of stoping or rifting off of blocks from the chamber vault or sides actually did take place to a certain extent at least, and this when the magma had cooled to a highly viscous condition and hence had comparatively little power to stope and too low a temperature to assimilate the blocks. Thus the occurrence of these xenoliths is quite in harmony with Daly's hypothesis.

SIGNIFICANCE OF THE MORE ACIDIC MASSES WITHIN THE STOCKS

As already mentioned, lighter colored, more acidic patches or masses sometimes occur within the gabbro stocks. These patches lack the diabasic texture of the inclosing gabbro and, instead of being in sharp contact with the gabbro, they rapidly grade into it. A good example is the stock $1\frac{1}{4}$ miles north-northeast of The Glen and represented by Nos. 7 and 8 in Table I, and another is stock No. 1 (see map) and represented by Nos. 9 and 10 in Table I.

Harker[1] admits the probability of stoping, but sees "no evidence of concomitant assimilation," and Iddings[2] says: "Evidences of absorption by the igneous magma of material from adjoining rocks are very slight. . . . . It commonly happens that blocks, or fragments of rocks, are inclosed in molten magma without exhibiting evidences of solutional reaction between the magma and inclosed rocks. . . . . Few statements as to signs of solution and diffusion of rock by igneous magmas have been substantiated by chemical evidence of a change in the intrusive magma due to such a reaction." Now, the writer believes that the more acidic patches or masses within the North Creek gabbro stocks do furnish strong evidence of chemical change within the intrusive igneous magma due to solution or partial solution and diffusion of blocks of country rock. In such cases the magma was just hot enough to melt or partially melt and only partially diffuse the blocks of country rock. Acidic masses formed in this way would not be expected to show

[1] *Natural History of Igneous Rocks*, p. 86.

[2] *Igneous Rocks*, I (1909), 281.

the diabasic texture. Obviously, examples of this kind would not be common.

The acidic (syenitic) border phase of stock No. 1 (see map) and represented by No. 10 of Table I might be explained on the basis of simple marginal assimilation, though there appears to be no good reason against explaining it as due to the assimilation of blocks of country rock stoped from the walls of the stock chamber. In accordance with Daly's hypothesis the blocks of country rock would have been derived from a level some distance above the present observed contact but, because of the low specific gravity of the country rock (granite) as compared with the molten gabbro, and also because of the superheated condition of this gabbro magma (as proved by the vigorous contact action on the granite), those blocks of country rock would not have sunk very far in the magma before they became thoroughly assimilated.

SIGNIFICANCE OF THE MORE ACIDIC STOCKS

Five or six of the stocks are composed of rocks more acidic than gabbro. Fine examples are: Stock No. 3 (see map); $1\frac{1}{3}$ miles northeast of Pottersville; $\frac{3}{4}$ of a mile south-southeast of South Horicon; and $1\frac{1}{4}$ miles southwest of The Glen. In fact every gradation may be found from stocks of basic gabbro, through acid gabbro and diorite, to syenite. In the earlier stage of very active intrusion the invading magma was more thoroughly molten, and as the blocks of country rock were stoped off they sank in the magma and became completely dissolved and diffused. Since the country rock was almost always granite, syenite, or gneiss, the magma became more and more acidic. A magma thus formed has been styled a "syntectic" magma. The amount of superheat required to dissolve the blocks would not be great because, as Daly has pointed out, there is plenty of proof that molten basic rock "even slightly superheated will dissolve fragments of gneiss and allied rocks. The mutual solution of two contrasted silicate mixtures takes place at a certain temperature which is lower than the melting-point of either one."[1] According to the specific

[1] *Amer. Jour. Sci.*, XXVI (1908), 36.

gravity figures given by Daly[1] on good authority it seems quite certain that most, at least, of the xenoliths would have sunk in the North Creek stock magmas during their highly molten early stages of intrusion.

The very close chemical relationship between the diabase and the typical gabbro pretty clearly shows the derivation of these rocks from a source of supply of such a basic composition, and that the acidic facies of the gabbro were somehow developed during the process of intrusion, more than likely by the assimilation of country rock. Where the normal basic rock now constitutes a stock is readily explained because in the later, less highly molten stage of intrusion, stoping would be greatly lessened and xenoliths would sink little if any, while this upward current of later basic magma would push the earlier formed, more acidic "syntectic" to a higher level in the vent. Where basic gabbro now fills a stock chamber simply means that the upper, more acidic assimilation product (syntectic) has been removed by erosion.

The objection may be raised that these stocks are too small to have had sufficient heat for the melting and diffusion of the xenoliths. But it must be remembered that the gabbro and its derivatives are true plutonic rocks, and that the portions of the stocks now at the surface were, at the time of intrusion, far below the surface. The fact that, in some cases, tongues of the intrusives have penetrated the country rock clearly argues for a highly fluid magma. Again, the very character of the distribution of the gabbros along distinct belts strongly suggests that the stock masses are merely offshoots from a much larger underground gabbro mass which, at the time of the intrusion, must have been more highly molten than the present surface exposures seem to indicate.

Thus the North Creek basic stocks appear to furnish fine illustrations of intrusions accompanied by more or less magmatic stoping and assimilation, so that we have all gradations from basic gabbro to syenite stocks, and from stocks in which magmatic assimilation produced true syntectic magmas, to those in which xenoliths were only partially dissolved and diffused, to those in which xenoliths were wholly undissolved.

[1] *Amer. Jour. Sci.*, XXVI (1908), 27–28.

LACK OF VARIATION OF THE DIABASE

Because of its remarkable homogeneity in composition, the diabase presents a marked contrast to the neighboring gabbro. The diabase never contains inclusions and never shows any evidence of magmatic assimilation even in the largest masses. This difference is quite certainly due to the difference in the mode and condition of intrusion, the diabase having clearly been forced through comparatively narrow fissures in the country rock and pretty near the earth's surface as the texture shows. In such intrusions magmatic stoping would be reduced to a minimum or absent.

"THE ORDER OF CRYSTALLIZATION IN IGNEOUS ROCKS"

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In a recent number of this *Journal* appeared an article entitled "The Order of Crystallization in Igneous Rocks."[1] A series of conclusions far-reaching in their effect on petrography are arrived at by the author, which are certainly worthy of further comment and discussion. By building up on certain fundamental assumptions, the author is enabled to give a series of diagrams showing for each of the important rock groups both the order of beginning and the order of cessation of crystallization. A further discussion of the assumptions seems, on account of the importance of the conclusions arrived at, very desirable.

In considering such a subject as the crystallization of a magma, we must first of all remember that we have to deal with a definite chemical system whose behavior is rigidly governed by the laws of mass action and the phase rule. The laws of physical chemistry should throw some light on this problem, and it is the purpose of the author to advance some ideas which may affect the conclusions arrived at in the above article.

Can we regard a granite and a rhyolite as representing the same chemical system? That is, may we in the full sense of the term regard a rhyolite as the quenched portion of the chemical system, which, if undisturbed, would result in a granite?

Geologists generally agree that the same magma, depending on certain variable conditions, such as temperature, pressure, and rate of cooling, may yield either a granite or a rhyolite, but probably none will maintain that these variable factors, and especially temperature and pressure, will have an effect only on the physical condition, but not also on the chemical condition of the magma. A granite consists not only of a solution of the various oxides in

[1] N. L. Bowen, *Journal of Geology*, XX, 455.

each other which subsequently enter into the formation of the different minerals in the rock, but there also enter in a series of volatile components such as water, boron, fluorine, chlorine, etc.—the mineralizers. How are these held in the magma? In all probability they are in certain molecular combination with some of the other oxides present. Under the conditions of great pressure and in the presence of mineralizers, a granite begins and completes crystallization. The effect of these volatile components is considered so important that the solidification temperatures of certain granites is placed as low as 200°–350° C.[1] These mineralizers are the powerful solvents, they represent to a large extent the "mother liquor" from which the granite crystallized.

Turn now to the case of a rhyolite. The variable factors are quite different. Pressure is far less, the rate of cooling is far more rapid. What will be the effect of such a change? In physical chemistry we recognize what is known as van't Hoff's law, which deals with the fact that displacements of equilibrium within a solution are effected by changes in temperature and pressure. Crystallization in a magma can be brought about in one case at a higher and in another case at a lower temperature, depending on the pressure. An increase of pressure will induce crystallization at a higher temperature. By a change of pressure equilibrium will be destroyed within the magma, and reactions taking place will go farther in one direction, thus altering the relative proportions of the various compounds present. As a result we may obtain in the rock an association of minerals quite different from what it would have been under a different pressure.[2] As a further result of decrease of pressure, the volatile constituents would escape, causing additional disturbance in the equilibrium and rearrangement in the molecular grouping, which will further influence the final crystallization product. Thus the law of mass action and van't Hoff's law seem to prove that granite and rhyolite cannot safely be regarded as having the same order of crystallization nor the same mineral make-up. The conception of mineralizers strengthens this view.

[1] Harker, *The Natural History of Igneous Rocks*, p. 189.

[2] Cf. C. N. Fenner, *American Journal of Science*, XXIX (March, 1910), 217.

If a solution crystallizes, is a recurrence of the first component to solidify possible, after complete crystallization of the other dissolved substances? We must concede as true that a magma represents a solution at high temperature, and that its crystallization must be analogous to the crystallization of any solution. Chemical precipitation due to chemical reaction caused by concentration, or by the elimination of some dissolved substance, may take place, but on the whole the analogy to a freezing salt solution should be striking. This has been pointed out repeatedly by various authors.

For comparison, let us recall Usiglio's classical experiments on the evaporation of sea-water. In this case we have a complex solution of such compounds as Fe_2O_3, $CaCO_3$, $CaSO_4$, NaCl, KCl, $MgSO_4$, $MgCl_2$, etc. Pressure and temperature were kept constant, but the degree of concentration was varied. The following order of crystallization was obtained: Fe_2O_3, $CaCO_3$, $CaSO_4+2\,H_2O$, NaCl, $MgSO_4$, $MgCl_2$, NaBr, KCl. There was an overlapping of the periods of crystallization, but in no case was there a recurrence of the crystallization of any member after a later product had formed (see fig. 1). When a salt solution freezes, ice crystallizes out, and the solution becomes more and more concentrated until saturation is reached (23.6 per cent NaCl); when at a temperature of $-22°$ C. both crystallize together, forming a cryohydrate. Salt does not crystallize out to be followed later by ice. Other examples of crystallization of salt solutions might be cited, but the above are sufficiently familiar and characteristic. In all cases (see Figs. 2, 3), however, no overlap of the first crystals formed can occur with regard to later products, as far as order of cessation of crystallization is concerned. In the majority of cases the end product should be a cryohydrate (eutectic).

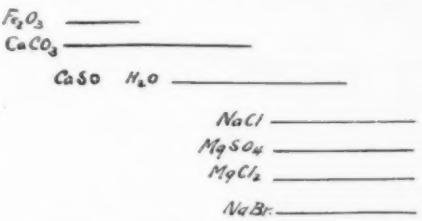


FIG. 1.—Order of crystallization upon partial evaporation of sea-water.

For a different case let us assume we have three metals fused into an alloy. Provided they are completely soluble in each other, the eutectic ratio is the controlling factor, the metal in greatest excess crystallizing first, until the second metal reaches its saturation point, when the two come down together, until finally the ternary eutectic point is reached and crystallization of all goes on simultaneously. In case the metals interact, chemical compounds may be formed and complicate the system. Thus in a combination

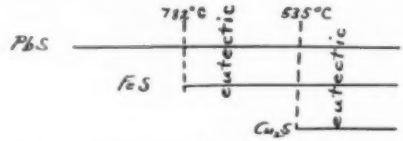


FIG. 2.—Order of crystallization in alloy of PbS = 70 per cent, FeS = 20 per cent, Cu_2S = 10 per cent.

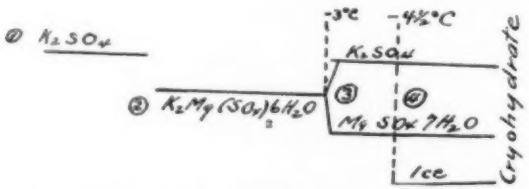


FIG. 3.—Crystallization of K and Mg sulphate solution, when K_2SO_4 is in excess and saturates solution between 92° and −3° C. Schönite ② is stable only between 92° and −3°C. See van't Hoff's *Theoretical and Physical Chemistry*, p. 86.

of bismuth, lead, and tin, the order of beginning of crystallization will depend on relative masses and will end with a ternary eutectic. In the case of a copper, tin, and antimony mixture, we get chemical reactions during cooling which may result in the formation of three pure metals and seven chemical compounds. There is no recurrence of the substance first crystallized in either case. If substances are capable of forming solid solutions they do not affect the above in any way.

For sake of simplicity let us assume we have a magma of SiO_2, $KAlSi_3O_8$, and $NaAlSi_3O_8$, an example worked out by Harker.[1]

[1] Harker, *Natural History of Igenous Rocks*, p. 251.

The order of crystallization will depend on relative masses, but will in every case end with a ternary eutectic. We all concede that the rate of growth of different crystals varies, but it does not seem probable that in the same solution one substance, such as quartz, begins solidifying before a second, say orthoclase, and also is still crystallizing after the latter is completely removed. Such overlapping would seem to be an unusual exception to the general rule, of which no example has been found. Considering this point, may we not assume that order of cessation of crystallization gives a definite clue to the order of beginning of crystallization?

SUMMARY

With a view of testing the conclusions as to order of crystallization, the author advances the following points:

1. We cannot assume that the effects of pressure and of crystallization temperatures may be considered negligible in the case of rhyolite and granite (effusive and deep-seated rocks). Therefore it is doubtful that we can assume the same order of crystallization or the same end-products.

2. We must recognize the importance of the mineralizers, not only as affecting the physical condition of the magma, but also its molecular arrangement, and consequently its manner and possibly, order of crystallization.

3. Comparing the order of crystallization in solutions and alloys, we find that the order of cessation of crystallization gives a definite clue as to the order of beginning of crystallization, consequently overlapping both of the beginning and the cessation of crystallization of any substance by another seems improbable.

The author is indebted to Professor M. F. Coolbaugh for valuable suggestions.

ANGISTORHINUS, A NEW GENUS OF PHYTOSAURIA FROM THE TRIAS OF WYOMING

MAURICE G. MEHL
University of Chicago

During the summer of 1904 a paleontological expedition from the University of Chicago, under the direction of Dr. S. W. Williston, made some valuable collections of vertebrate fossils from the Trias of Wyoming along the Popo Agie River. From these collections Dr. Williston described *Paleorhinus bransoni* and mentioned three other phytosaurian skulls,[1] all of which were collected by Drs. E. B. Branson and R. L. Moodie. Dr. Williston has very kindly granted the writer the permission to study these phytosaurs and it is from this material that the following notes are drawn. Considerable time and patience have been required of Mr. Paul C. Miller in the preparation of two of these skulls for mounting and the work is not yet completed. In all probability it will be some time before a full description with figures of these specimens is possible and for this reason it seems advisable to give a brief diagnosis of a new form represented by them for the benefit of others that may be studying this group of reptiles.

Angistorhinus grandis, GEN. AND SP. NOV.

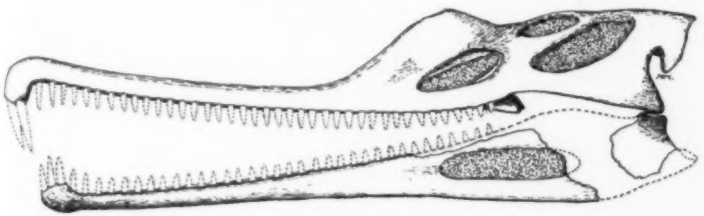
This form is represented by a nearly complete skull and a mandible of which the right ramus, back of the symphysis, is missing, as is a small part of the left ramus. Many limb bones, dorsal plates, and other fragments were found in the same locality with the skull and may belong to this species.

In a lateral view the skull resembles very closely that of *Mystriosuchus* Fraas.[2] The premaxilla, as in *Mystriosuchus*, are

[1] "Notice of Some New Reptiles from the Upper Trias of Wyoming," *Jour. Geol.*, XII (1904), 696.

[2] *Die Schwabischer Trias-Saurier nach dem Material der Kgl. Naturalien-Sammlung in Stuttgart zusammengestellt* (1896), p. 16, Pl. V.

produced into a long, slender, subcylindrical rostrum. Near the anterior end the rostrum expands rather rapidly and is bent abruptly downward at right angles to the axis of the posterior portion. This downward extension reaches a distance of 35 mm. below the ventral plane of the rostrum. The anterior border of the nares is about even with the anterior border of the antorbital vacuity and about 590 mm. from the tip of the rostrum. The nares are elevated on a prominence that extends slightly above the plane of the inter-orbital region. This prominence is accentuated by a saddle-shaped depression immediately back of the nares. The antorbital vacuities are large and are oval in outline, about 130 mm. long and 55 mm. wide. The orbits are separated by an inter-orbital space of 68 mm. They are oval, about 89 mm. long and 55 mm. wide, and their



Skull and mandible of *Angistorhinus grandis*. Lateral view, about one-ninth natural size.

planes are directed outward and a little less upward. The latero-temporal fenestrae are exceptionally large, being about 171 mm. along the greatest diameter. They reach back and upward to such an extent that only a narrow bar of bone separates the supra-temporal and the latero-temporal fenestrae. The supra-temporal fenestrae are large, more or less oval in outline, about 84 mm. long and 46 mm. wide. The posterior border, the parieto-squamosal arcade, is well developed. It is formed by a rather broad, platelike bone (the sutures have not yet been made out) that lies in the plane that extends over the posterior dorsal surface of the skull. The posterior border of the skull, as seen from above, is incised by a broad, rather deep notch. Still, the posterior border of the parietals at the median line extends beyond the occipital condyle fully 11 mm. The downward extension of the postero-lateral portion of the

squamosal of *Mystriosuchus planirostris* has an even greater development in this form. The hooklike process in *A. grandis* extends below the plane of the dorsal surface of the skull a distance of about 104 mm. Although all the teeth but the roots of the anterior ones have dropped from the alveoli, a fairly good idea of the dentition can be gained. The downward extension of the rostrum contains four teeth, sections of the roots of which show a diameter of about 15 mm. The anterior teeth of another specimen (described below), although of less diameter, reach a length of about 78 mm., a fact that would bespeak a still greater length for the anterior teeth of *A. grandis*. Sections through the rostrum disclosed teeth that had not yet been erupted. These, as many others found loose in the matrix, were laterally compressed with anterior and posterior sharp, finely serrate, cutting edges.

The differences between *Angistorhinus* and the forms that it resembles seem evident. From *Mystriosuchus* it differs in possession of laterally compressed posterior teeth with sharp, more or less serrate cutting edges. Quoting Dr. E. Fraas (*op. cit.*, p. 16): "Die Zähne selbst sind auch nicht glatt und mit scharfer Kante versehen, sondern schwach gerieft und von rundem Querschnitt ohne Kante, sie gleichen am meisten den *Nothosaurus*-Zähnen aus den Bonebeds. Dass eine Species mit derartigen Zähnen nicht gut *Belodon* (Pfeilzahn) genannt werden kan, wird man mir zugaben."

McGregor has characterized not only *Mystriosuchus*, but the entire suborder, Phytosauria, as having the parieto-squamosal arcade greatly reduced and depressed.[1] In *Angistorhinus* this is decidedly not the case; the arcade is well developed and lies in the plane of the posterior dorsal surface of the skull.

From *Rhytidodon carolinensis* Emmons[2] *Angistorhinus* differs considerably in the development and position of the parieto-squamosal arcade, for *Rhytidodon* and *Mystriosuchus* seem to be very similar in this respect. To quote Dr. McGregor (*op. cit.*, p.

[1] *Memoirs of the Amer. Mus. of Nat. Hist.*, IX, Part II (1896), 92.

[2] This is the genus and species recognized by McGregor (*ibid.*, p. 95). F. von Huene (*Beiträge zur Kenntnis und Beurteilung der Parasuchier*, 1911, p. 42) has included *Rhytidodon* in the genus *Mystriosuchus*, but Emmons' genus seems to stand, as the teeth are shown by McGregor to be laterally compressed, some with cutting edges, whereas, as pointed out above, the teeth in *Mystriosuchus* are all round in cross-section.

58): "In this specimen [a specimen of *R. carolinensis* from the U.S. Nat. Mus.] the broad superficial portion of the post-fronto squamosal arcades is broken away, exposing the supratemporal fenestra and the parieto-squamosal arcade. If uninjured this portion of the skull would closely resemble that of *Mystriosuchus*. . . . ."

There is no good basis for the comparison of *Angistorhinus* with *Phytosaurus* (*Heterodontosuchus*) *ganei* Lucas,[1] as until recently only the anterior part of an imperfect mandible of the latter form was known. In this, according to Lucas, the teeth were separated by a thin film of bone only, while in *Angistorhinus* they are separated by a distance of from 4 mm. to 8 mm. Furthermore, the examination of more recently obtained material suggests, at least, that *Heterodontosuchus* belongs to the genus *Phytosaurus* (McGregor, *op. cit.*, p. 94). In this case the differences in the posterior border of the skulls would exist as pointed out above.

Angistorhinus differs from *Paleorhinus bransoni* Williston[2] in many minor points such as the greater posterior width of the skull in the former, the greater lateral extent of the opisthotics, the larger openings in the skull, the abrupt downturning of the anterior end of the rostrum, and the much more massive build of the skull throughout. Most important of the differences, however, is the more primitive, that is, the more anterior position of the external nares in *Paleorhinus*. In that form the posterior border of the nares lies fully 30 mm. in front of the anterior borders of the antorbital vacuities, while in *Angistorhinus* the anterior border of the nares is about even with the anterior borders of the antorbital vacuities.

While *Angistorhinus* resembles *Mesorhinus Fraasi* Jaekel[3] in the form and development of the parieto-squamosal arcade, the two forms differ markedly in that the latter possesses a parietal foramen, according to Jaekel, and has the external nares more anterior in position. The downward process from the upper posterior side of the squamosal seems to be lacking in *Mesorhinus*, and the basi-

[1] *Amer. Jour. Sci.* (4), VI (1898), 399.

[2] J. H. Lees, *Jour. Geol.* XV, No. 2 (1907).

[3] "Uber einen neuen Belodonten aus dem Buntsandstein von Bernburg," *Sitzungsberichten der Gesellschaft Naturforschender Freunde*, No. 5, Jahrgang 1910.

cranial region seems to extend back much farther than in *Angistorhinus;* to such an extent, in fact, that the basioccipital is plainly visible in a dorsal view in the former. The following table of measurements of *Angistorhinus grandis* may be found useful in comparing it with other forms.

Greatest length of skull	977 mm.
Length of skull from quadrates to tip of rostrum	909
Length from nares to tip of rostrum	590
Length from anterior borders of orbits to tip	755
Inter-orbital width	68
Greatest width of skull about	390

Another specimen of *Angistorhinus* is represented by a skull, the mandible, and apparently a nearly complete skeleton. The posterior end of the mandible and the upper posterior part of the skull are missing, but these may be contained in the unpacked slabs. In general appearance this specimen is the counterpart of *A. grandis* though smaller and more slenderly built. It can hardly be considered a young individual of *A. grandis*, however, as some of the following differences in the rostrum will show. In the second specimen the slender rostrum starts much more abruptly in front of the antorbital vacuity than in *A. grandis*. While the smaller skull is considerably compressed laterally, and lateral measurements are, therefore, of less value than longitudinal ones, the rostrum seems but little affected by this compression and the following measurements seem to show the differences well. At a point 140 mm. in front of the antorbital vacuity the width of the rostrum is about 56 mm. (some allowance is here made for compression), while at the same distance in front of the antorbital vacuity in *A. grandis* the width is about 94 mm. This is exactly the opposite of what one would expect if the former specimen were but the young and the latter the adult of the same species. In *A. grandis* the terminal expansion is just back of the downward extension and the expanded portion includes but four teeth. In the smaller specimen, however, the expansion takes place suddenly just back of the second tooth behind the downward extension and from this point to the extremity the lateral outlines of the rostrum are approximately parallel. Eight teeth are included in the anterior expanded part

of this rostrum, four on each side. On the right side three of these are preserved. The first, the posterior one of these, reaches a length of 69 mm. The second is missing. In the downward extension the lateral tooth is 78 mm. long and the inner one, probably a young tooth, is about 35 mm. long.

The anterior end of the mandible is expanded in a horizontal plane, while in that of *A. grandis* the sides of the anterior expansion are turned up, thus forming a deep, rounded groove along the median line. The terminal expansion in each form bears three large teeth with approximately circular section. Immediately back of these large terminal teeth the diameter of the teeth in *A. grandis* is from 7 mm. to 9 mm., while in the second specimen the diameter is from 5 mm. to 7 mm. In much probability further study will show that the skulls belong to two different species.

Reviews

Earth Features and Their Meaning. An Introduction to Geology. By William H. Hobbs. New York: Macmillan, 1912. Pp. xl, 506 illustrations, maps, appendices, index.

While the subtitle would class the book with texts in geology the first title is much more appropriate, and suggests the author's unique point of view. The work should be classed with Geikie's *Earth Sculpture* and Marr's *Scientific Study of Scenery*, but it is much more ambitious. The author has here expanded the substance of his own course of lectures on the subject in the University of Michigan.

As a textbook in geology it endeavors to cover only dynamic and structural geology. In the thirty-one chapters these two fields are well covered. The figure of the earth and its materials are described, and then discussed as to origin, nature, and interpretation. Rock structures, after careful description, are analyzed to get at their history, and to discover their effect on topography. The "character lines" of forms due to weathering, streams, ground water, waves, glaciers, sun and wind without much rain, and diastrophism are described, genetically correlated, and illustrated by line drawings, block diagrams, and sketches from photographs. Rarely are photographs reproduced without adapting by cutting out the non-essential and presenting in lines and symbols the essential. Twenty-four plates—photographs—against about 500 figures are used.

With a conscious effort to illustrate the theoretic work from American features the author has, possibly unconsciously, given a rather large place to glaciers, 140 pages out of about 500. No other overweighting seems apparent.

The introduction of much experimental data, and the forcing of the reader to go out and see things mentioned constitute a very valuable feature. Extended lists of reading references at the end of each chapter put the reader in touch with much of the best literature on the various topics. Appendices for the determination of minerals and rocks, and for the preparation, interpretation, and care of topographic and geologic maps are followed by a list of suggested itineraries for geologic study both in America and in Europe.

The student of physiography will find much more than the geologist in the work. The boundary line between the two sciences is pretty well concealed. Physiography is made to contribute to geologic interpretation and a wealth of data are furnished, ready to be applied to the elucidation of stratigraphic problems. G. D. H.

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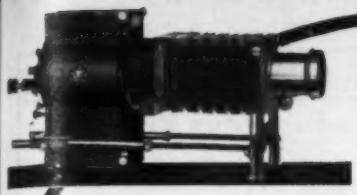

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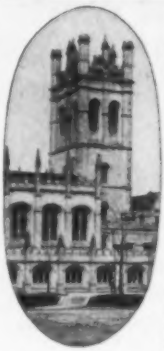

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